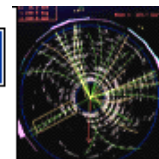# The CDF Experiment for Run II at the Tevatron

Arnd Meyer, Fermilab / RWTH Aachen
Royal Holloway
February 10, 2003

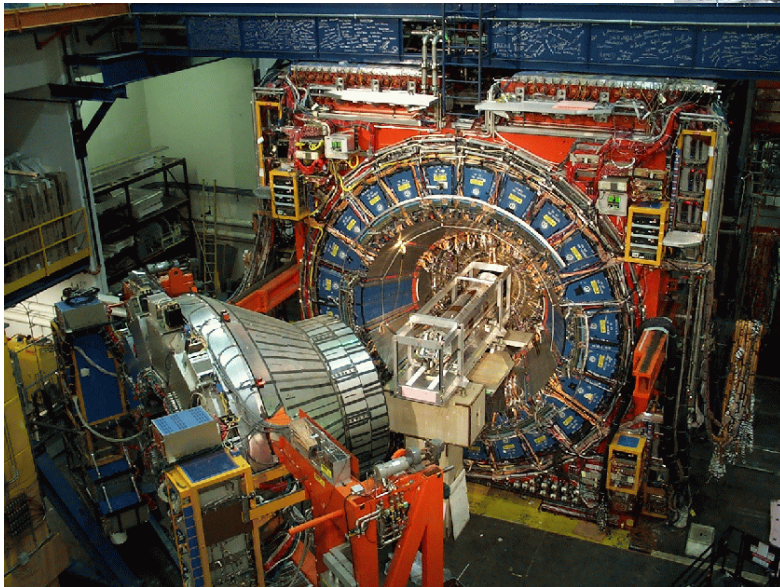**Fermi National Accelerator Laboratory**

inquiring minds

Outline

- The Fermilab accelerator complex
- The CDF II detector
  - Tracking, particle ID
  - Data acquisition and trigger
- Goals for Run II

- First results
  - A few appetizers
- Summary

Fermilab Accelerator Complex

Fermi National Accelerator Laboratory: commissioned in 1967, operated by the Universities Research Association under contract of US-DOE
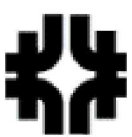
- ● Fermilab Tevatron

  - ♦ Superconducting proton-antiproton collider

  - ♦ R = 1km, E_{beam} = 1TeV, B = 4.5T

  - ♦ 36 colliding p and pbar bunches

  - ♦ $N \cdot 10^{11}$ ($N \cdot 10^{10}$) p (pbar) per bunch

- ● "Run I" 1992-1996: Discovery of the top quark (1995)

- ● Goal: *A high beam-beam crossing rate but with <N> ≃ 1 collisions per crossing* (expect 1-10)

Booster

C D F

Tevatron

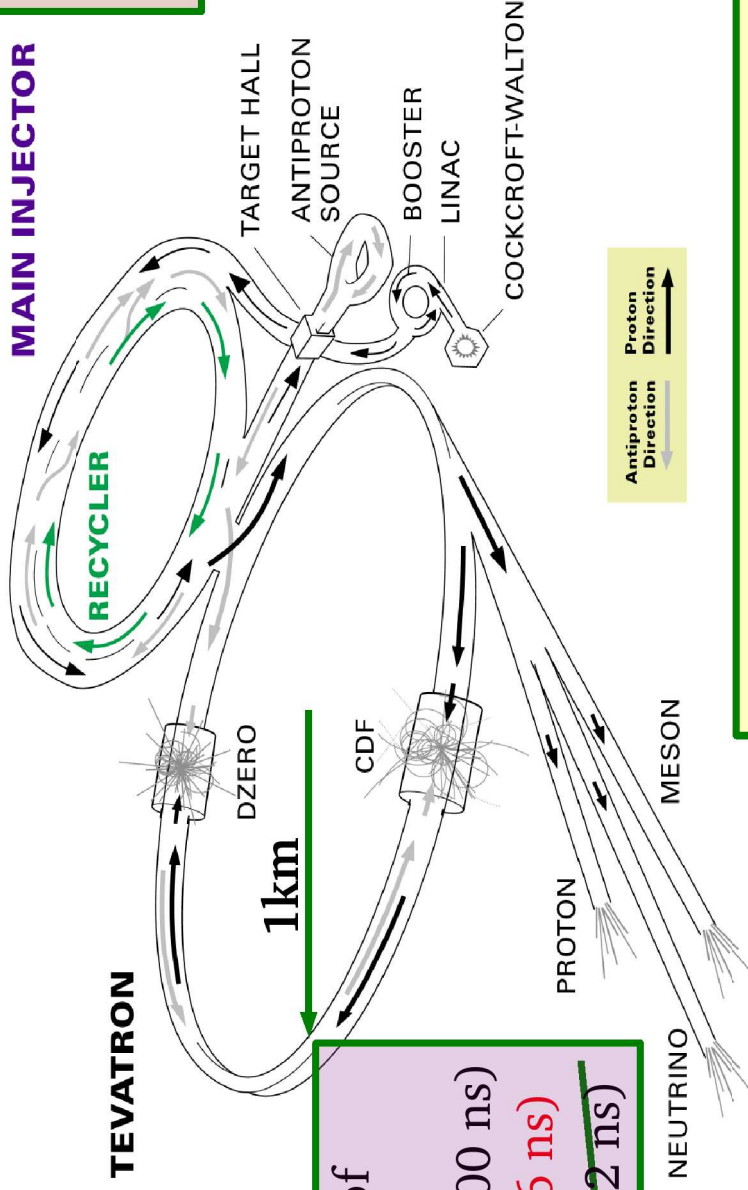p̄ source

Main Injector and Recycler
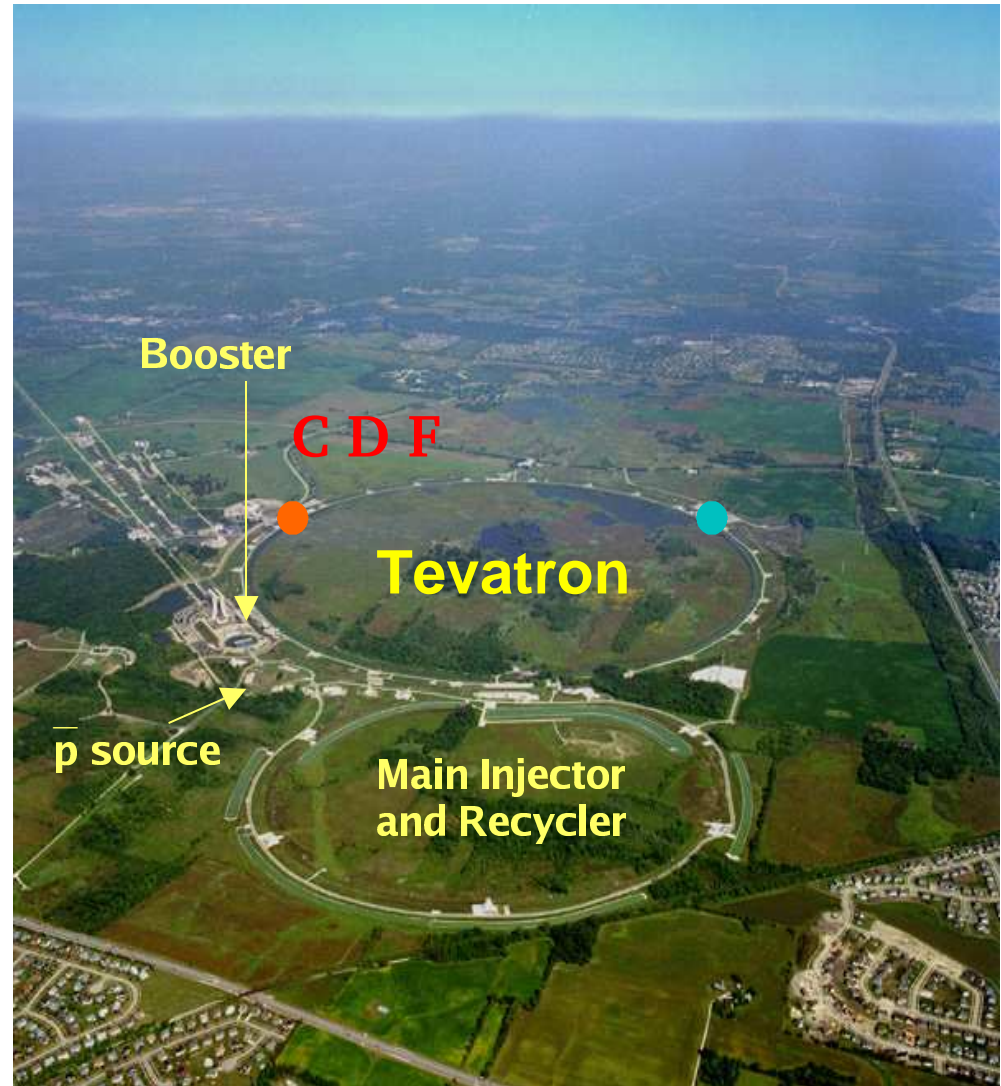
Accelerator Upgrades

$\overline{p}p$ collisions at $\sqrt{s} = 1.96$ TeV
(up from 1.8TeV)

Main Injector
(p storage ring up to 150GeV)
replaces Main Ring: x5

Recycler storage ring for antiprotons: factor 2-3 in luminosity (2003-4)

New cooling for antiprotons
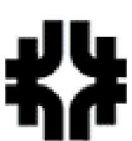
2005++: electron cooling, crossing angle, electron lens, luminosity levelling, ...: factor 2-3

Increased # of bunches:
6 (3500 ns)
→ 36 (396 ns)
→ ~100 (132 ns)

FERMILAB'S ACCELERATOR CHAIN

MAIN INJECTOR

RECYCLER

TEVATRON

DZERO

CDF

1km

TARGET HALL

ANTIPROTON SOURCE

BOOSTER

LINAC

COCKCROFT-WALTON

PROTON

MESON

NEUTRINO

Antiproton Direction   Proton Direction

February 10, 2003

Arnd Meyer (Fermilab)

Accelerator Upgrades cont.

$$L = \frac{fBN_p N_{\bar{p}}}{2\pi(\sigma_p^2 + \sigma_{\bar{p}}^2)} F(\sigma_l / \beta^*)$$

- More protons
- More antiprotons
- Higher $\bar{p}$ production rate
- Smaller bunch spacing

$\Rightarrow$ **Higher luminosity**
Comparable number of interactions per crossing
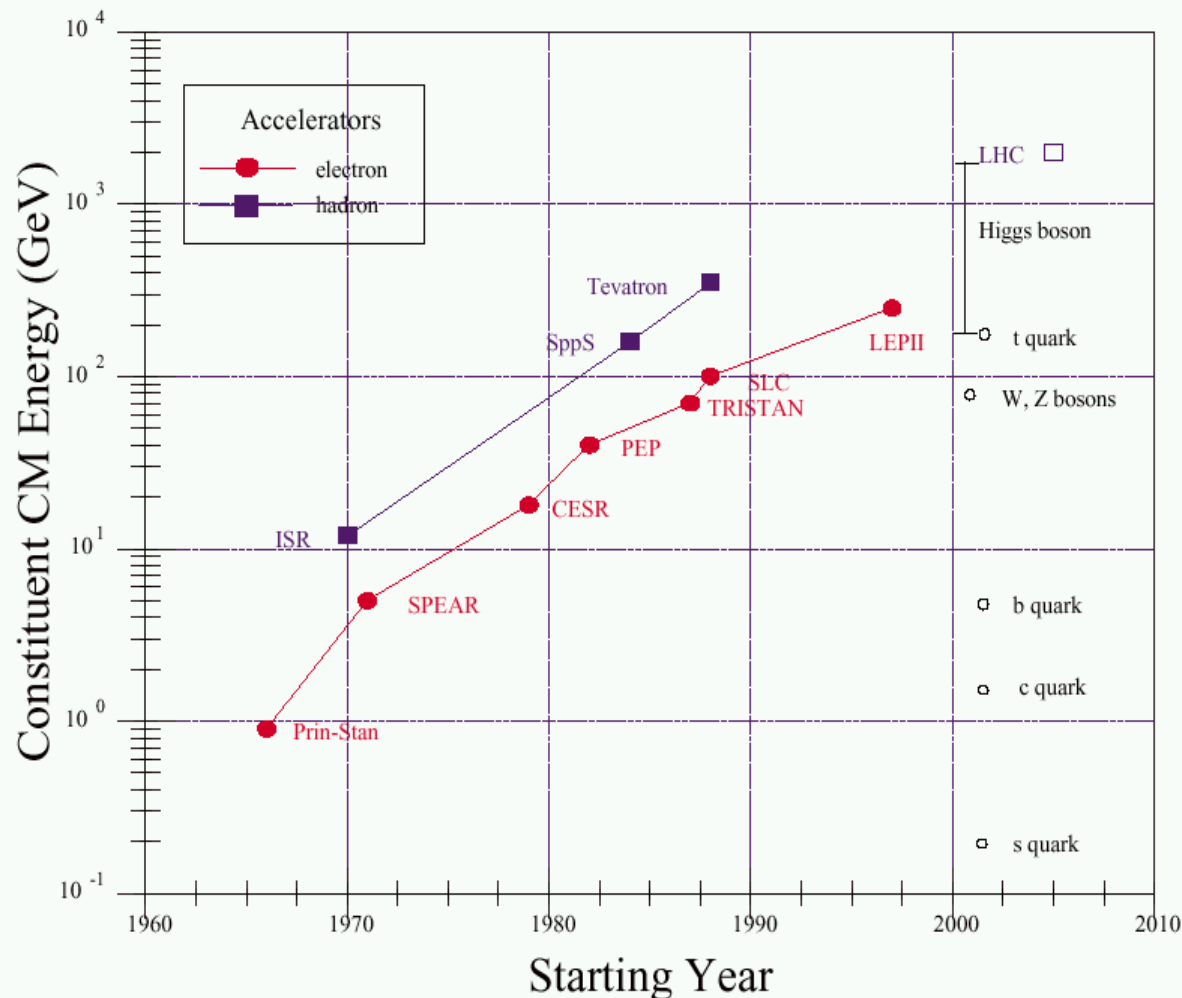
- Initial peak luminosity

     $1.6 \cdot 10^{31} \mathrm{cm}^{-2}\mathrm{s}^{-1}$ (Run I)

     $\rightarrow\ 8 \cdot 10^{31} \mathrm{cm}^{-2}\mathrm{s}^{-1}$ (Run IIa, 2003)

     $\rightarrow\ 2 \cdot 10^{32} \mathrm{cm}^{-2}\mathrm{s}^{-1}$ (Run IIa + Recycler)

     $\rightarrow$ up to $4 \cdot 10^{32} \mathrm{cm}^{-2}\mathrm{s}^{-1}$ (Run IIb)

- Run IIa: $\int L\, dt \simeq 2\ \mathrm{fb}^{-1}$ by the end of 2004 (factor 20 compared to Run I)

- Run IIb $\int L\, dt \simeq 10 - 15\ \mathrm{fb}^{-1}$ (2006 $\rightarrow$ "LHC physics")

- Accelerator luminosity is driven by physics goals

Why Collide Hadrons?

Emphasis on maximum energy = maximum reach for new discoveries

- **Advantages**
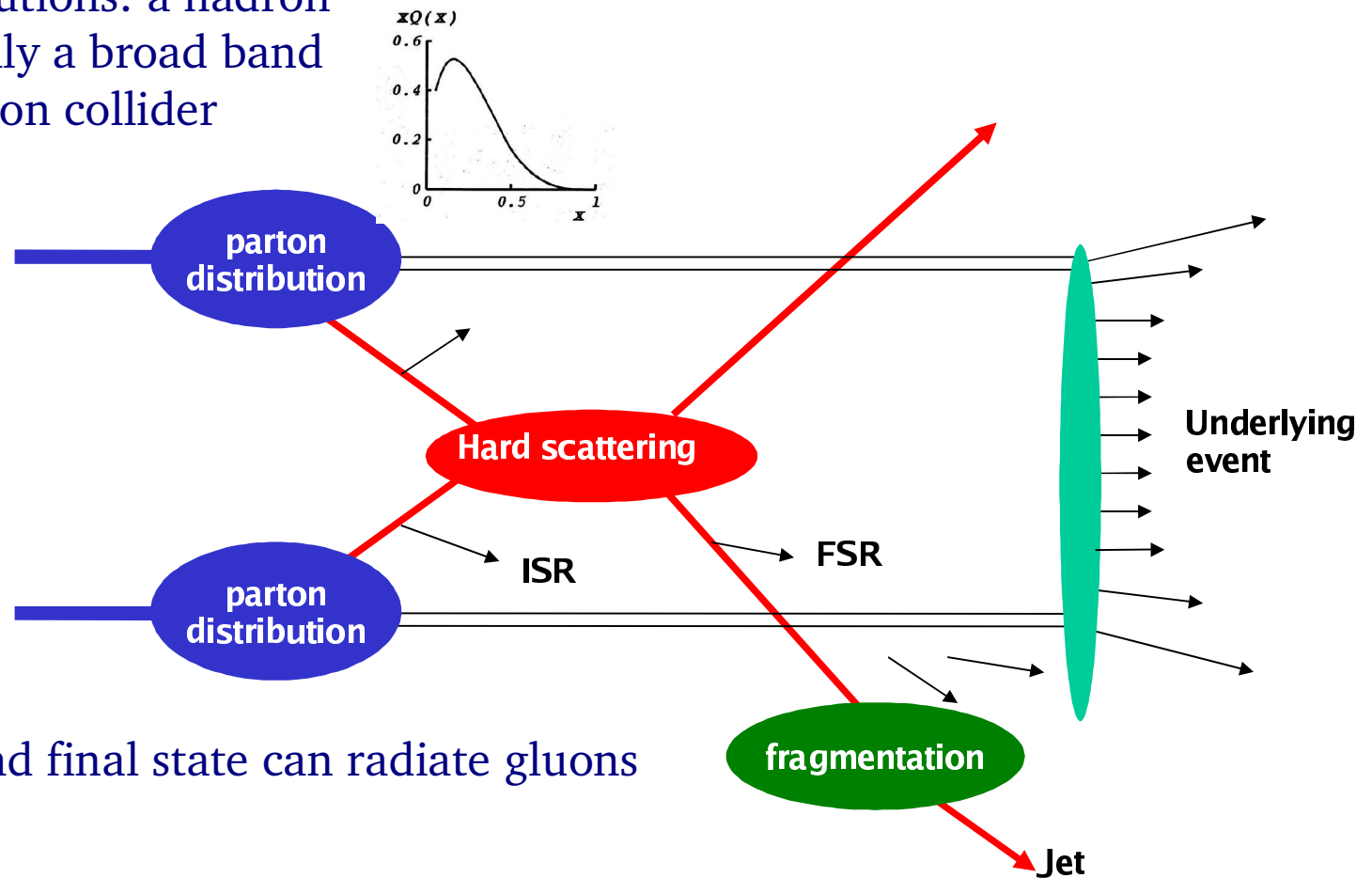 - ♦ Accelerating protons to high energies is easy

- **Disadvantages**
  - ♦ Creating/storing antiprotons is complicated
  - ♦ Or, collide p-p at the cost of a second ring
  - ♦ Quarks and gluons are strongly interacting → collisions are messy (but broad range of energies!)

Hadron-Hadron Collision

- Parton distributions: a hadron collider is really a broad band quark and gluon collider


$xQ(x)$

- Initial and final state can radiate gluons

- Underlying event from proton remnants

parton distribution

parton distribution

Hard scattering

ISR

FSR

fragmentation

Underlying event

Jet

Hadron Collider Variables

- The incoming parton momenta are unknown, and usually the beam particle remnants escape down the beampipe

 ♦ Longitudinal motion of the centre of mass cannot be reconstructed
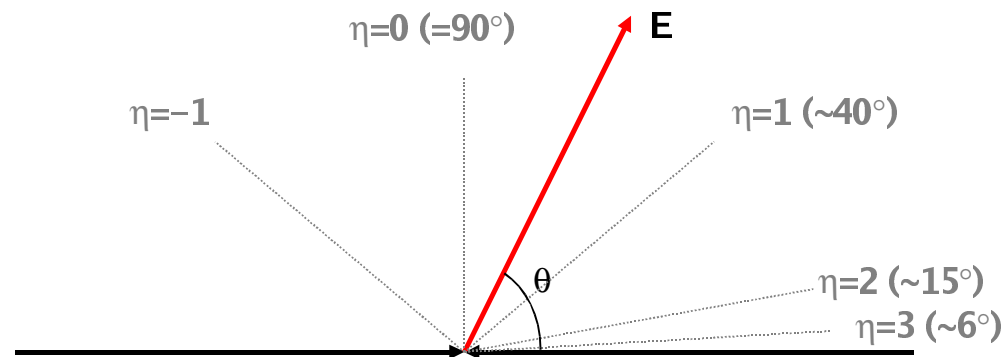
- Focus on transverse variables

  ♦ "Transverse energy" $E_T = E \sin \theta$ (=p_T if mass=0)

- And longitudinally boost-invariant quantities

  ♦ Pseudorapidity $\eta = -\log(\tan \theta/2)$ (=rapidity y if mass=0)

  ♦ Particle production typically scales per unit rapidity

Challenge and Reward

- Higher energy
- Broadband production

⇒ Discovery machines

- Physics cross section high
- What's interesting is rare
- Ability to find rare events is a consequence of sophisticated detector design

  ◆ Multi-level trigger systems and high-speed pipelined electronics

  ◆ Precision, high-rate calorimetry

  ◆ High-rate tracking detectors

  ◆ Radiation tolerant Silicon micostrip detectors

CDF II

Muon System

Time-of-Flight

Central Calor.
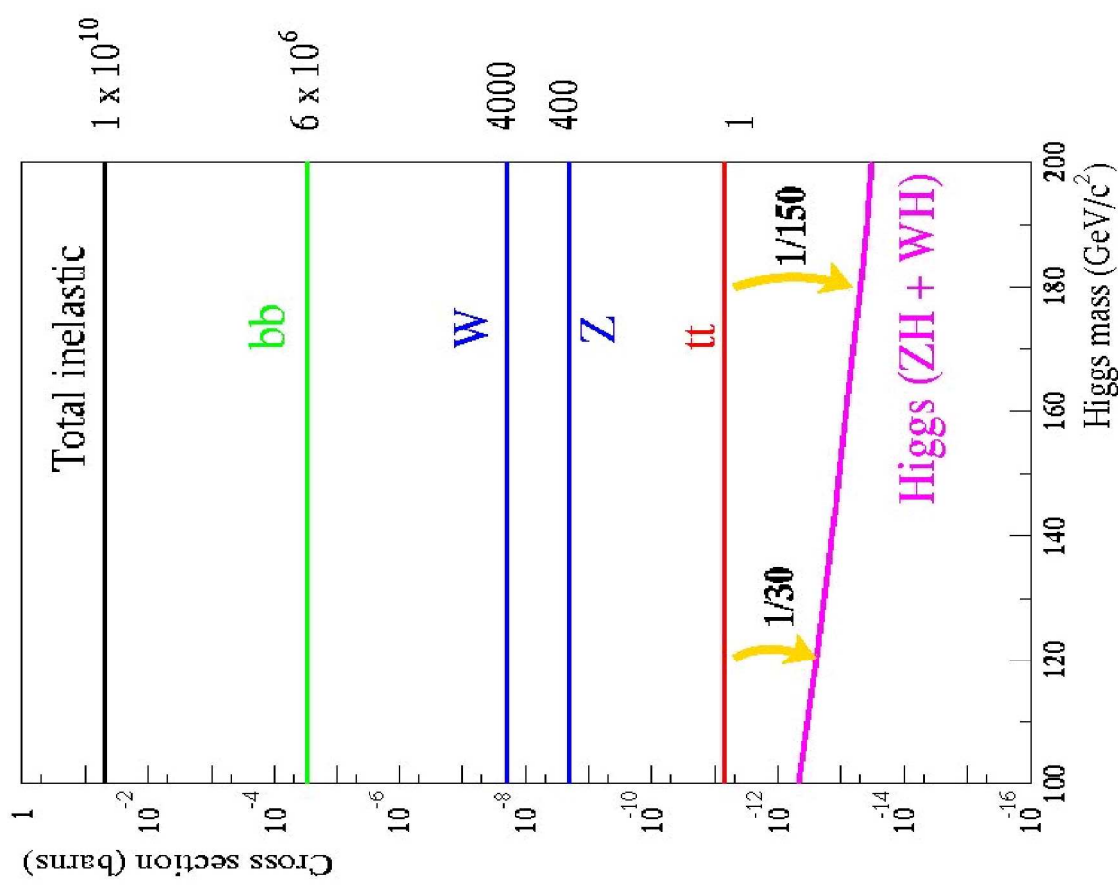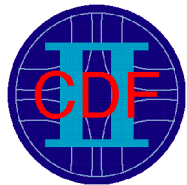
Solenoid

New
Old
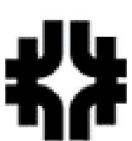Partially New

Miniplug

Plug Calor.

Drift Chamber

Silicon Microstrip Tracker

Muon

Front End Electronics
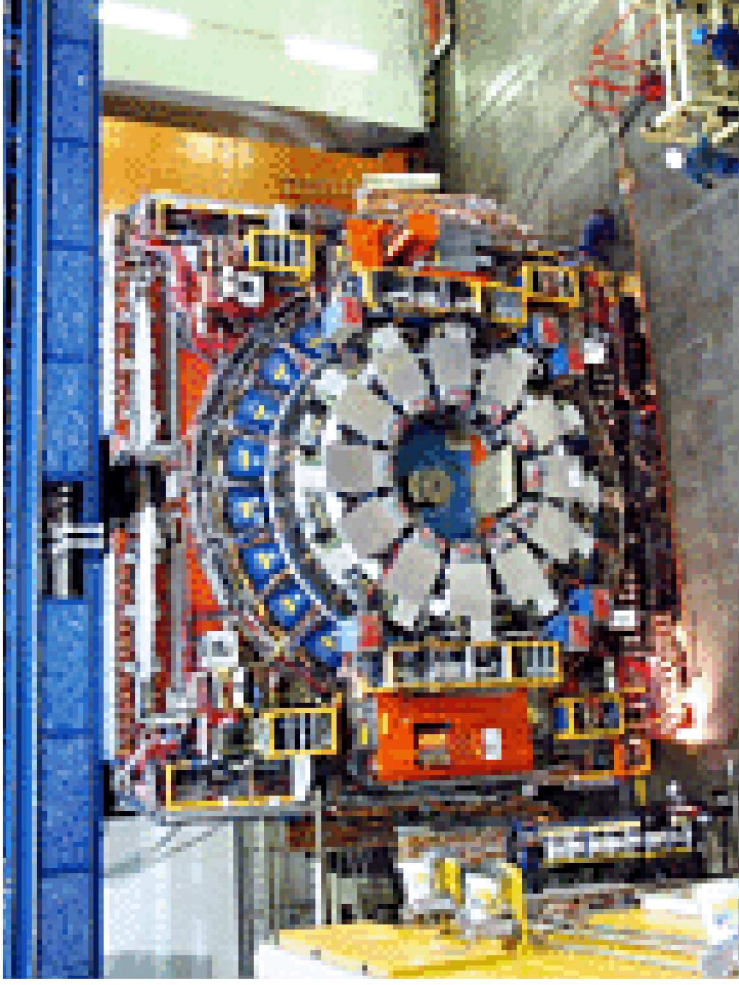Triggers / DAQ (pipelined)
Online & Offline Software
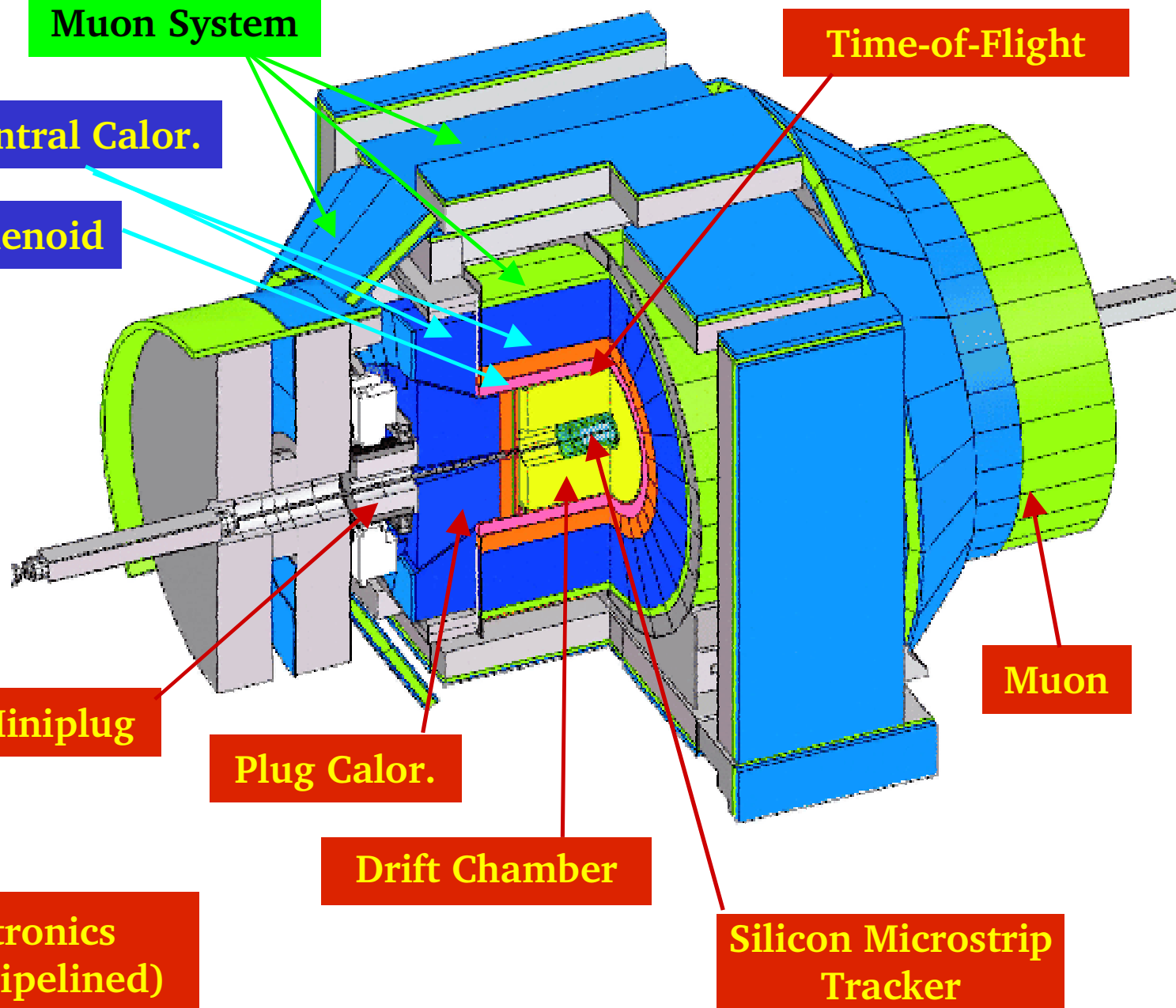
Experiment Status

- Run II started in April 2001 – stable physics running established early 2002

    - All major components commissioned by February 2002, using ~20 pb^{-1} of data

- Up to $\int L \, dt \simeq 20$ pb^{-1} of "physics quality data" used in ICHEP analyses

    - Expect about 70 pb^{-1} for "ski" conferences – the "blessing" marathon has just started
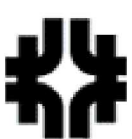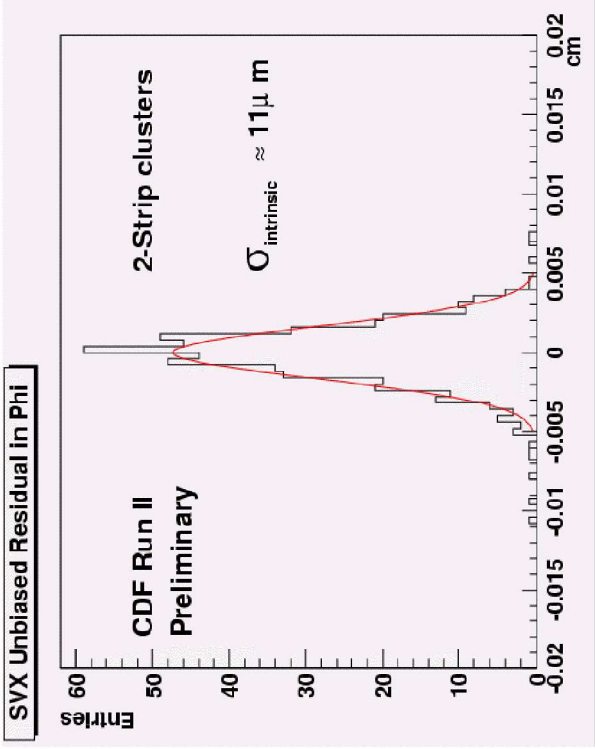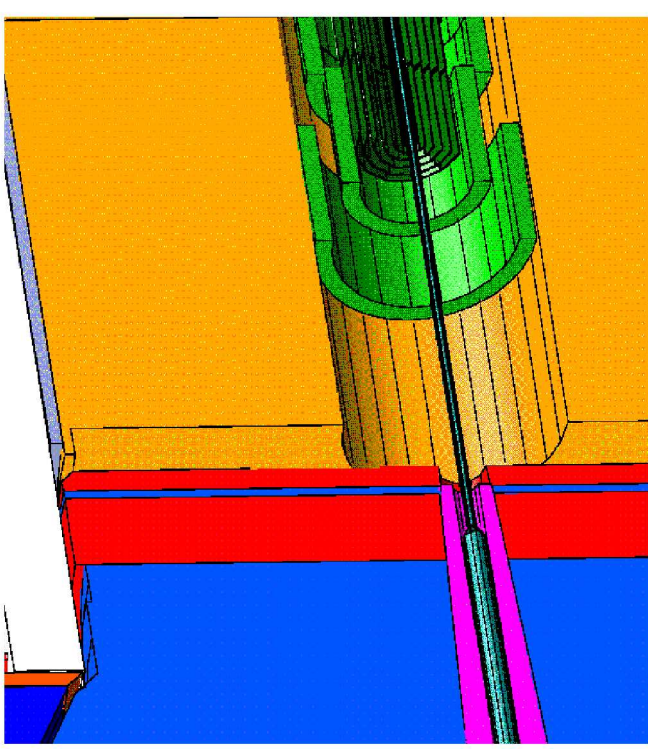
Detector roll-in February 2001

Tracking System: Silicon Detectors

- Three parts:
  L00, SVXII (feeds Silicon Vertex Trigger), ISL

- $|\eta| < 2$, $|z| < 45$cm

- Overall twice the acceptance of the Run I Silicon

- Essential for tagging of long-lived particles
  ($c\tau(B) \simeq 460\mu m$)

2b's or not 2 b's?
Double tags essential for M_{top}, $H \rightarrow bb$

CDF	Layer 00	SVX II	ISL	Totals
Layers	1	5	2	8
Length	0.9 m	0.9 m	1.9 m	
Channels	13824	405504	303104	722432
Modules	48 SS	360 DS	296 DS	704
Readout Length	14.8 cm	14.5 cm	21.5 cm	
Inner Radius	1.35 cm	2.5 cm	20 cm	1.35 cm
Outer Radius	1.65 cm	10.6 cm	28 cm	28 cm
Power	~100 W	1.4 kW	1.0 kW	2.5 kW

SVX Unbiased Residual in Phi

CDF Run II
Preliminary

2-Strip clusters

$\sigma_{intrinsic} \approx 11\mu m$

Central Outer Tracker

- **New Detector & Electronics**

  - ♦ **Smaller cell size** (4x # of cells), max drift distance $\simeq$ 1cm

  - ♦ **100ns maximum drift time** with fast gas (Ar-Et-CF$_4$ 50:35:15)

  - ♦ **8 superlayers x 12 wires** = 96 space points; 30240 sense wires

- 40<r<140cm, hit resolution $\simeq 175\mu$m

- **Measured single track efficiency 100% for high p$_T$ isolated tracks**

- **315 multi-hit TDC boards** in 20 crates, 1ns resolution

- 96 channels per board

- On-board trigger/DAQ buffering, DSP for hit processing

- Also used in other systems, total $\simeq$ 500 boards

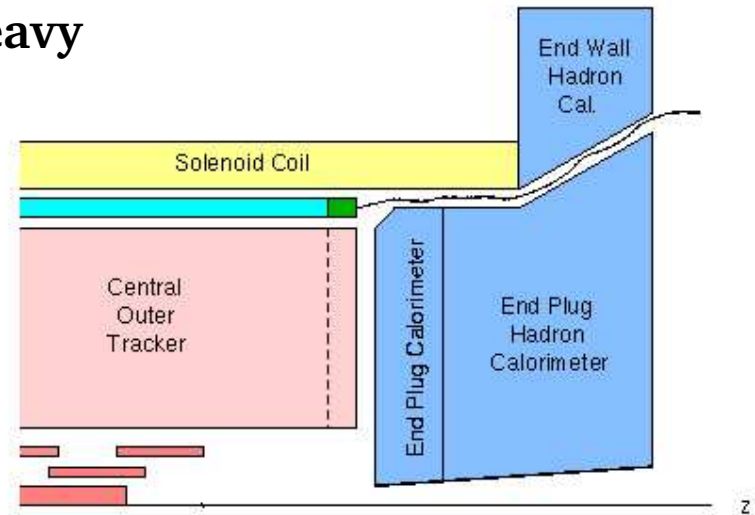
TDC Module

XFT TDC Mezzanine module
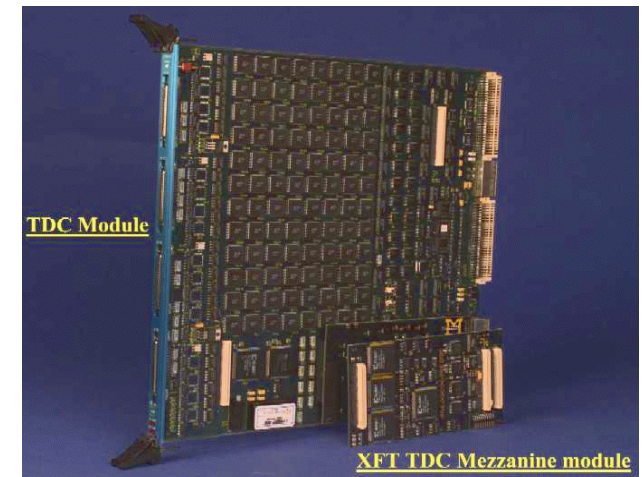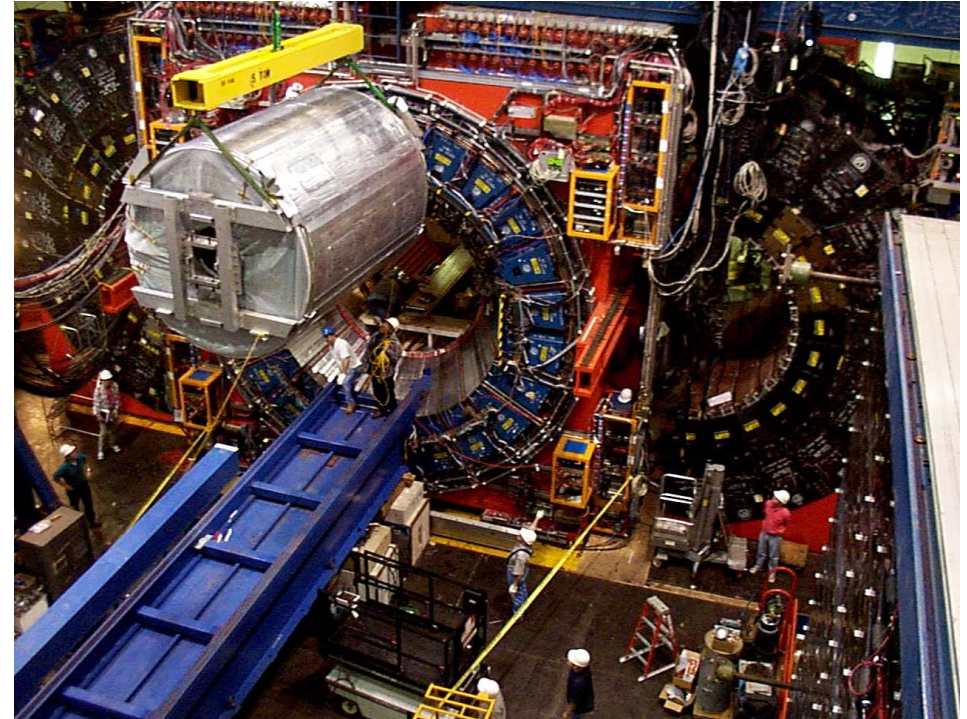
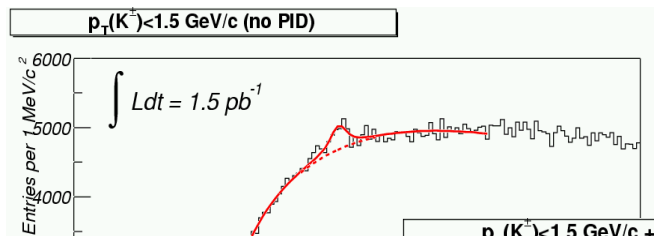**Particle ID is a typical weak point of doing heavy quark physics at a hadron collider!**

<u>TOF scintillator bars</u>

216 x 2 PMT channels at R=1.4m
100ps timing resolution (125ps achieved)

Tag low pt Kaons in $\phi \to KK$

End Wall
Hadron
Cal.

Solenoid Coil

Central
Outer
Tracker

End Plug Calorimeter

End Plug
Hadron
Calorimeter

z

$p_T(K^+)$<1.5 GeV/c (no PID)

$\int Ldt = 1.5\ pb^{-1}$

Entries per 1 MeV/c²

S/N ~ 1/40

$p_T(K^+)$<1.5 GeV/c + PID

$\int Ldt = 1.5\ pb^{-1}$

$|\Delta t_K/\sigma_t|$<3

Entries per 1 MeV/c²

S/N ~ 1 / 2

$N(\phi) = 1942 \pm 93$
$N(bkg) = 4517$
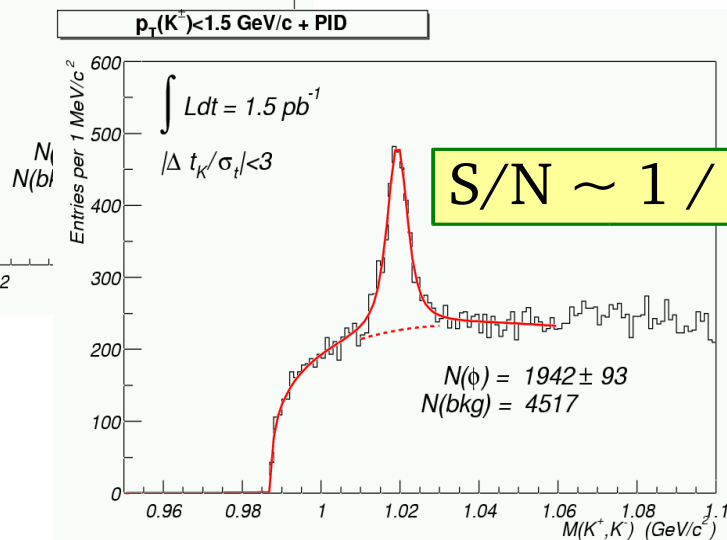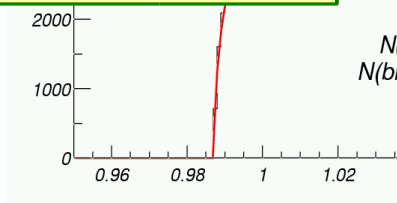
$M(K^+,K^-)$ (GeV/c²)

CDF Time-of-Flight : Tevatron store 860 - 12/23/2001

$p/c\sqrt{1/\beta^2 - 1}$ (GeV/c²)

p

K

π

Momentum (GeV/c)
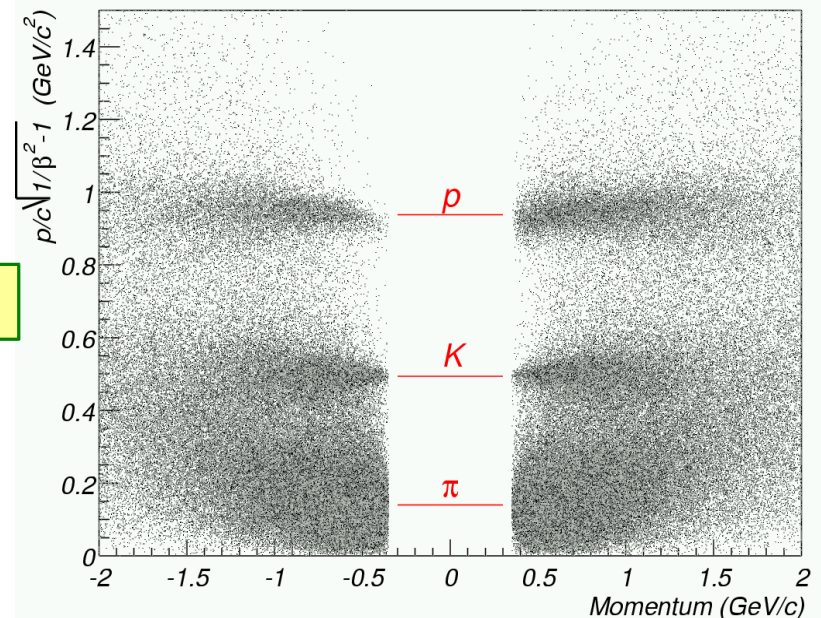
DAQ, Trigger, Electronics

- Almost completely replaced to operate with shorter bunch spacing (132 ns) and to handle higher data volume and rate

- One of the biggest upgrade projects for CDF

- Unique triggering capabilities for B physics

- Front-end and trigger electronics are housed in ~125 VIPA VME crates, 21 slots 9U x 400mm. ~ Half on detector, ~ half in counting rooms

  ♦ **Over 1700 main modules of about 60 types** (+ >400 spares)

  ♦ Over 1000 transition (I/O) modules of about 25 types

  ♦ 60 - 6U Eurocard crates with >700 modules for Showermax readout and clock system

  ♦ Over 25000 daughter boards
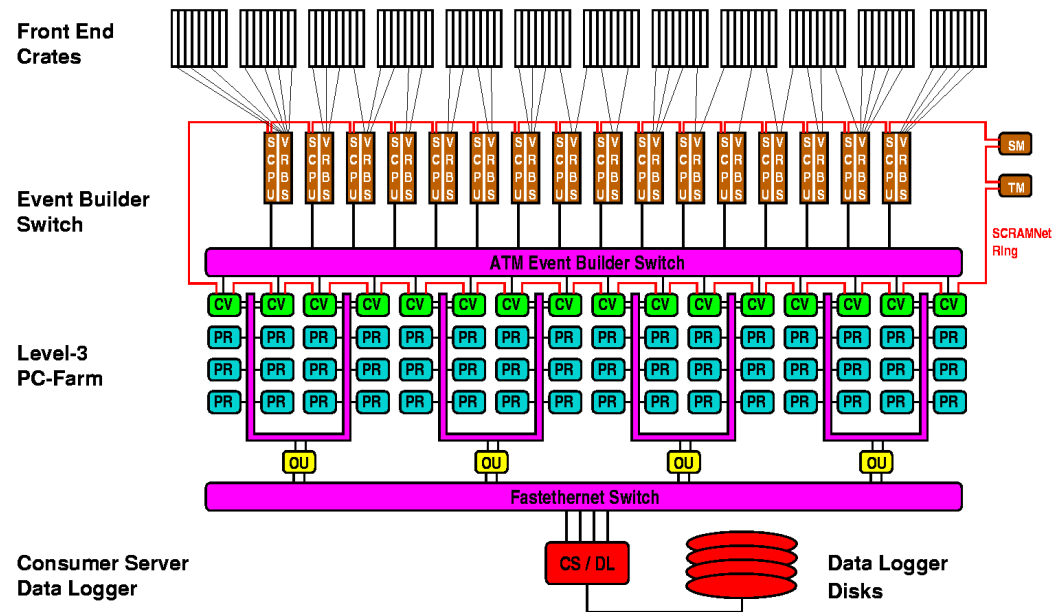
Trigger Overview

- **Level 1 (5.5μs latency) :**
  - ♦ Every front-end system stores data for 42 crossings
  - ♦ "Hardware trigger"
  - ♦ 50kHz accept rate (currently 12kHz)
  - ♦ On L1 accept, data is stored in one of four L2 buffers. Si readout starts.
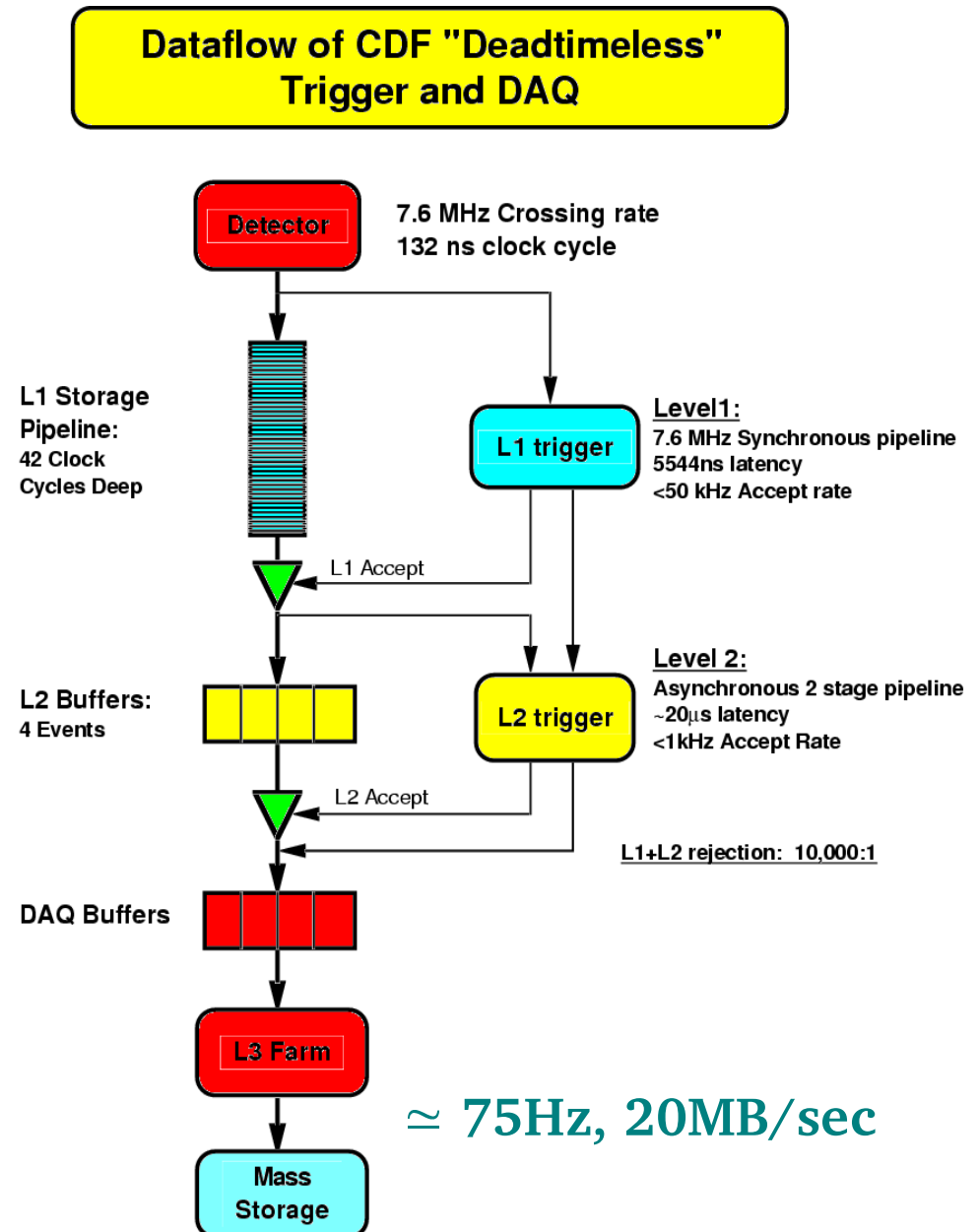
- **Level 2 (asynchronous):**
  - ♦ Nominal 20μs decision time
  - ♦ "Mostly hardware" trigger
  - ♦ Trigger algorithms run on custom Alpha boards (up to 4)
  - ♦ 300Hz accept rate ($\rightarrow$ 1kHz)
  - ♦ Event readout starts on L2A

- **Level 3:**
  - ♦ $\simeq$ 250 dual-CPU Linux boxes

- *"Deadtimeless"*: DT only incurred when all L2 or DAQ buffers are full

Dataflow of CDF "Deadtimeless" Trigger and DAQ

Detector — 7.6 MHz Crossing rate, 132 ns clock cycle

L1 Storage Pipeline: 42 Clock Cycles Deep

Level1:
7.6 MHz Synchronous pipeline
5544ns latency
<50 kHz Accept rate

L1 trigger

L1 Accept

L2 Buffers: 4 Events

Level 2:
Asynchronous 2 stage pipeline
~20μs latency
<1kHz Accept Rate

L2 trigger

L2 Accept

L1+L2 rejection: 10,000:1

DAQ Buffers

L3 Farm

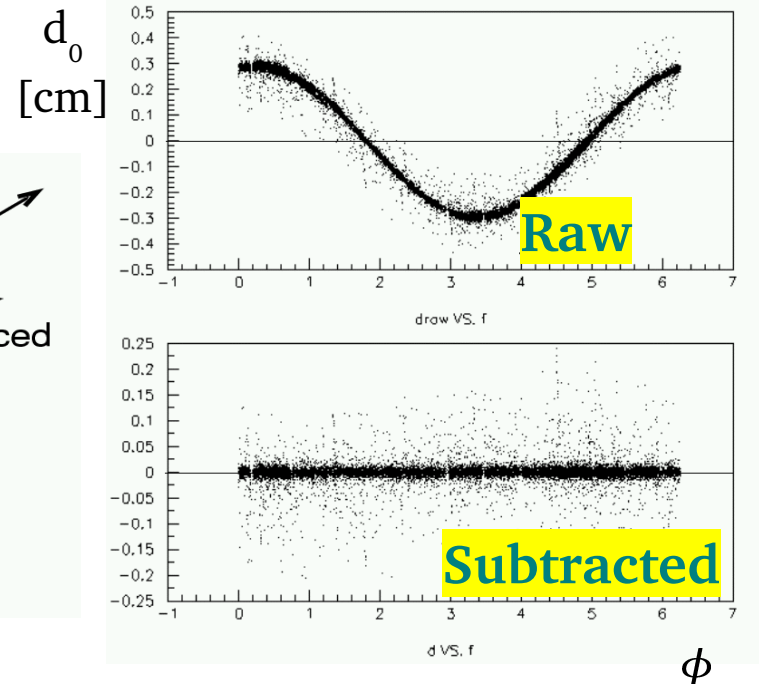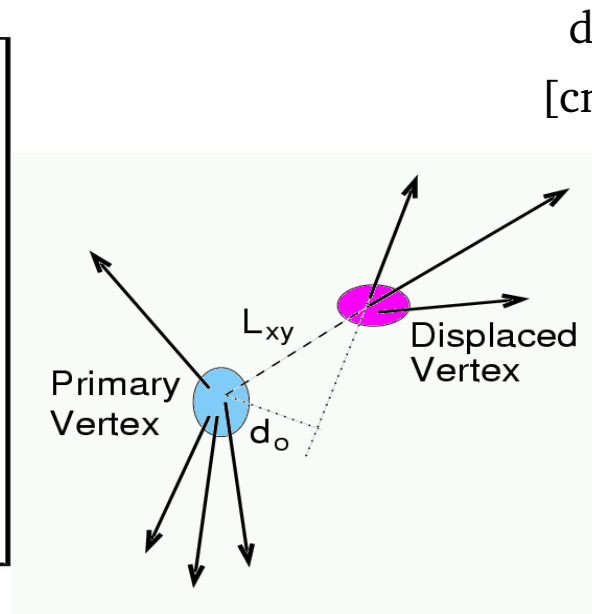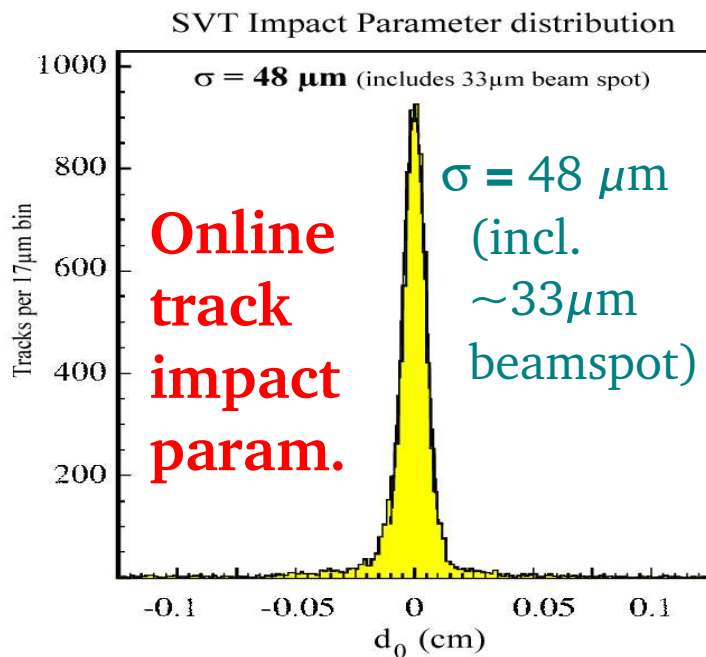$\simeq$ 75Hz, 20MB/sec

Mass Storage

L2: Silicon Vertex Tracker

- Major rate reduction at L2 from revolutionary **<u>displaced vertex trigger (SVT)</u>**

- Seeded by L1 (drift chamber, eXtremely Fast Tracker) tracks, ~150 VME boards find and fit Silicon tracks, with offline accuracy, in a $15\mu s$ pipeline

- Many important physics signatures involve b quarks: Higgs searches, top studies
- Allows purely hadronic B trigger, e.g. $B^0 \to \pi^+\pi^-, B_s \to D_s\pi$

Online fit and subtraction of beamline!

d_0 [cm]

Online track impact param.

SVT Impact Parameter distribution

$\sigma = 48\ \mu m$ (includes $33\mu m$ beam spot)

$\sigma = 48\ \mu m$ (incl. $\sim 33\mu m$ beamspot)

Tracks per 17μm bin

d_0 (cm)

L_{xy}

Primary Vertex

Displaced Vertex

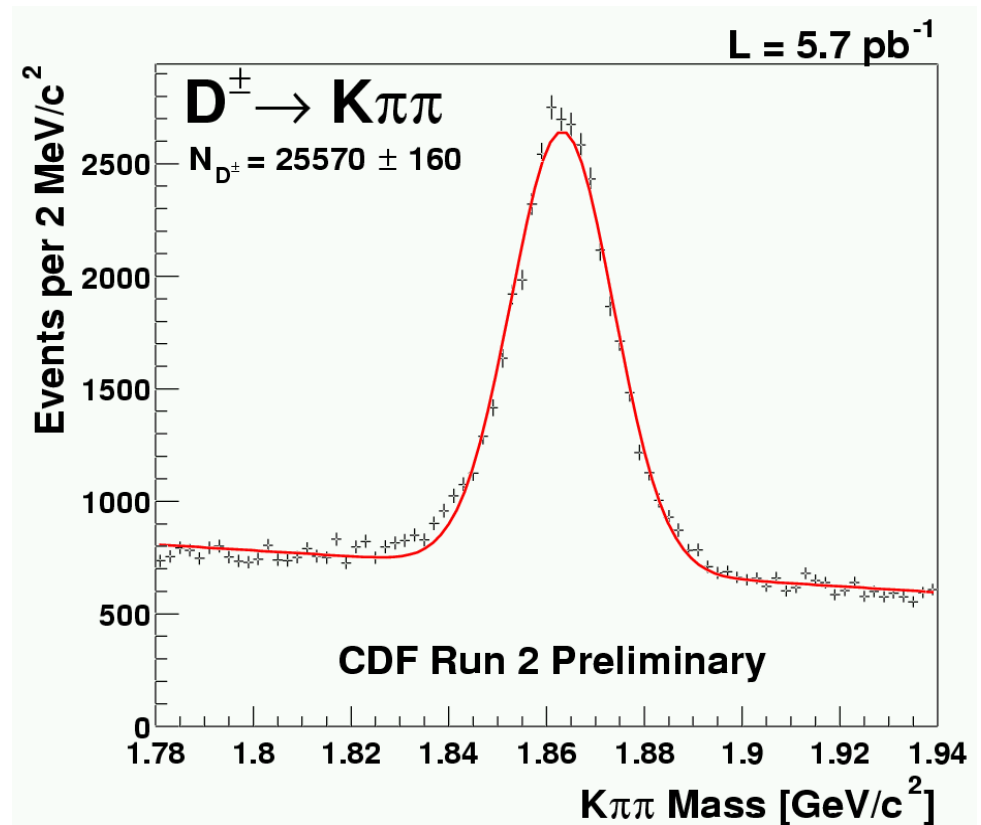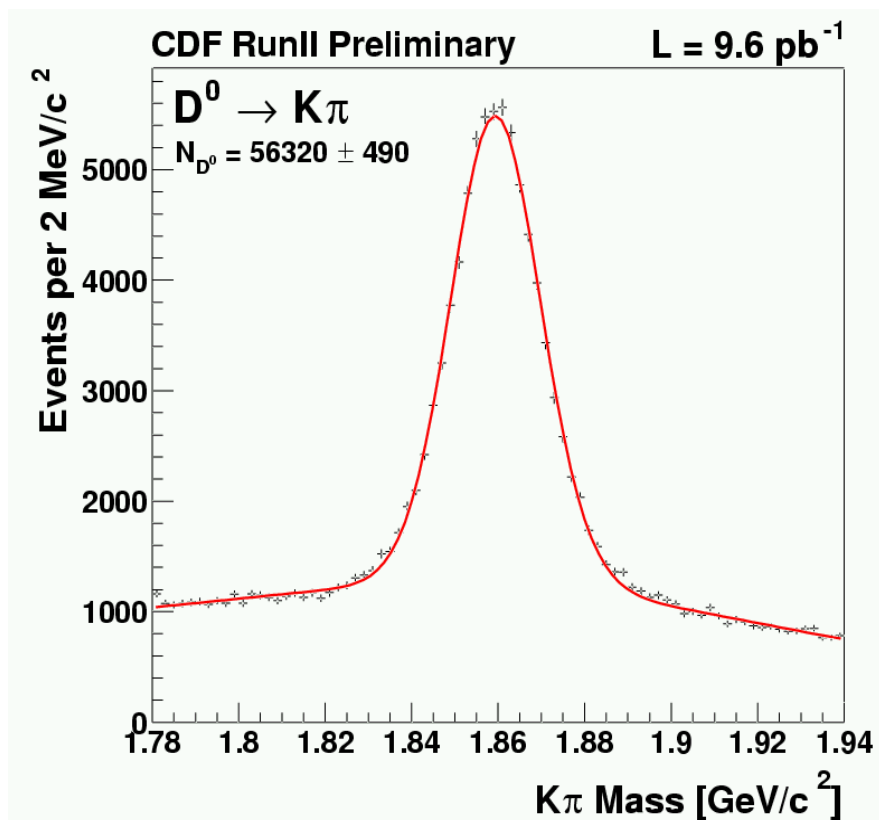d_0

Raw

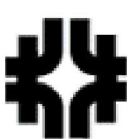drow VS. f

Subtracted

d VS. f

ϕ

Charm Production

- Accumulating large amounts of charm final states through hadronic "B" trigger

  - L1: >2 XFT tracks, p_T > 1.5 GeV

  - L2: >2 SVT tracks, p_T > 2.0 GeV, d_0 > 120μm
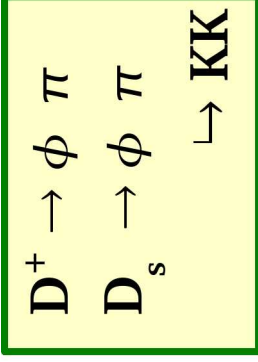
No lepton was harmed in the making of these plots!

D_s, D^+ Mass Difference

Some are born to discover J/ψ, some achieve photoproduction of charm, and some have charm physics thrust upon 'em

- Entirely new possibilities opened up by SVT

- Example: $m(D_s)-m(D^+)$, enters the global **PDG fit for all charmed meson masses**

- Reconstruct both mesons in the decay channel $D \to \phi \pi$

  $$D^+ \to \phi \, \pi$$
  $$D_s \to \phi \, \pi$$
  $$\hookrightarrow KK$$

  - ◆ kinematically very similar

  - ◆ many systematics cancel

- D_s mass comes out right:

  $m(D_s) = 1968.2 \pm 0.3$ MeV (fit)

  $m(D_s) = 1968.6 \pm 0.5$ MeV (PDG)

CDF Run II Preliminary
D^+, $D_s \to \phi\pi$, $\phi \to KK$
Unbinned likelihood fit projected

~1330

~2350

Entries per 2 MeV/c^2

$KK\pi$ mass [GeV/c^2]

$$m(D_s) - m(D^+) = 99.28 \pm 0.43 \, (stat) \pm 0.27 \, (syst) \text{ MeV}$$

(PDG: 99.2 ± 0.5 MeV)

CDF Run II Physics Goals

- Two main goals

  - ♦ Find the Higgs

    - – 5σ discovery seems possible for low mass Higgs

    - – Exclusion up to 180GeV with $\simeq$10 fb^{-1}

  - ♦ Direct evidence of something beyond the Standard Model, e.g. SUSY partners
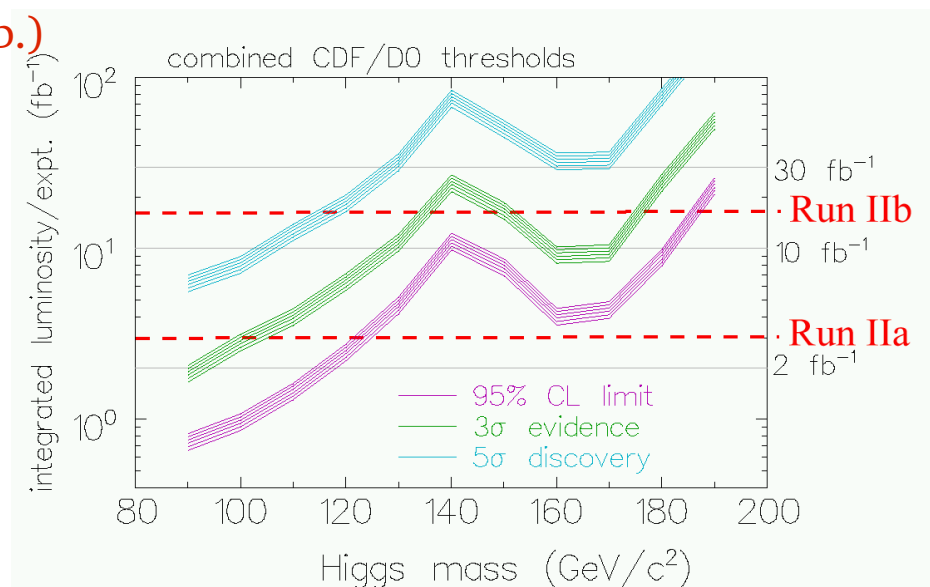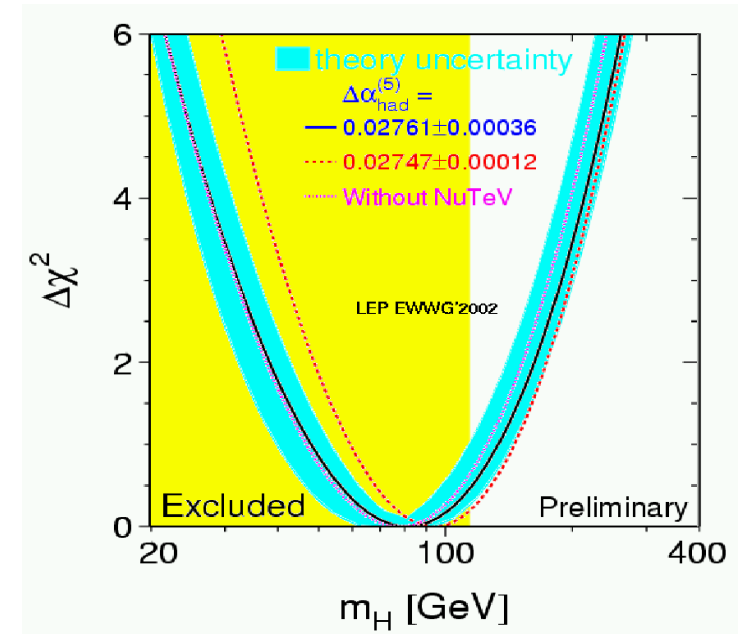
- Precision top / electroweak measurements

  - ♦ E.g. Higgs Bounds from m_W and m_t

  - ♦ $m_t = 174.1 \pm 5.1$ GeV (Run I CDF+D0 comb.)
    $$\rightarrow \pm 4 \text{ (Run 2a)} / \pm 2 \text{ (Run 2b) GeV}$$

  - ♦ $m_W = 80.452 \pm 0.062$ GeV
    $$\rightarrow \pm 35 \text{ (Run 2a)} / \pm 20 \text{ (Run 2b) MeV}$$

- B physics

  - ♦ CKM matrix and CP violation, B_s mixing
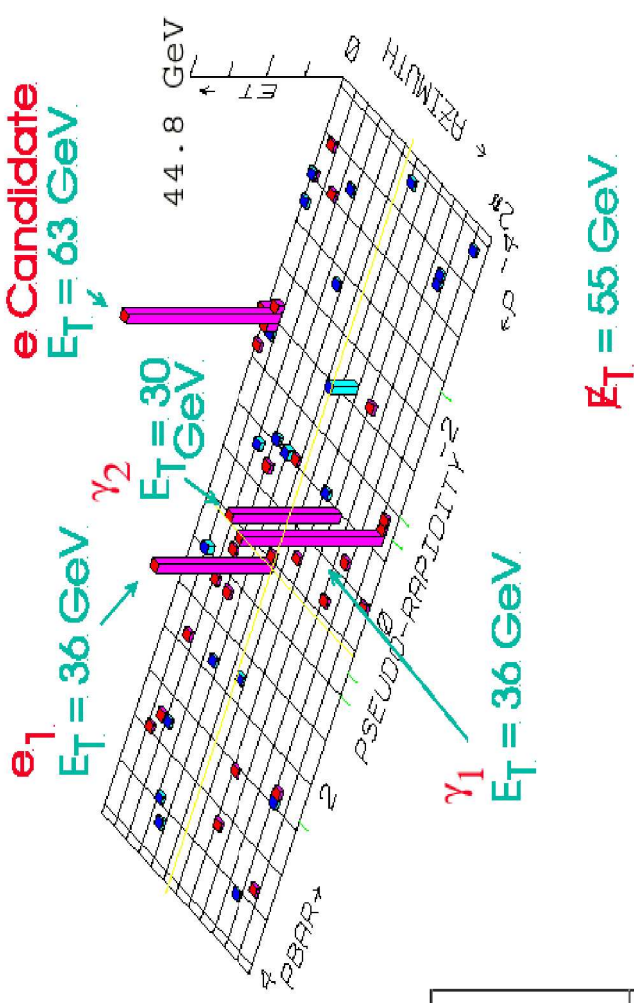
- ... as well as more exotic fare

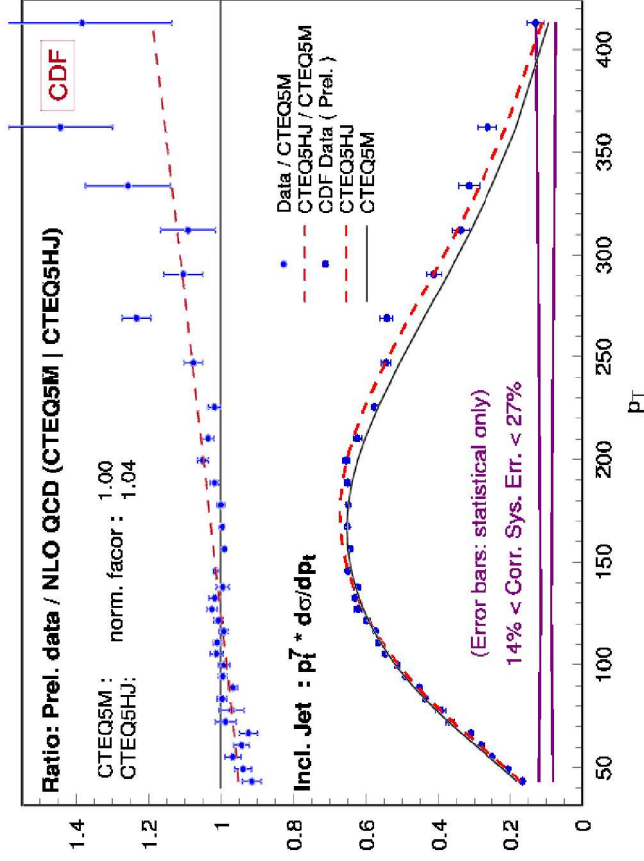 - ♦ Large extra dimensions, mini black holes

CDF Run II Physics Goals

ee$\gamma\gamma$$\not{E}_T$Candidate Event

44.8 GeV

AZIMUTH

e Candidate
E_T = 63 GeV

γ_2
E_T = 30 GeV

e_1
E_T = 36 GeV

γ_1
E_T = 36 GeV

$\not{E}_T$ = 55 GeV

PSEUDO-RAPIDITY 2

$\bar{P}BAR$ →

Follow up on Run I anomalies!

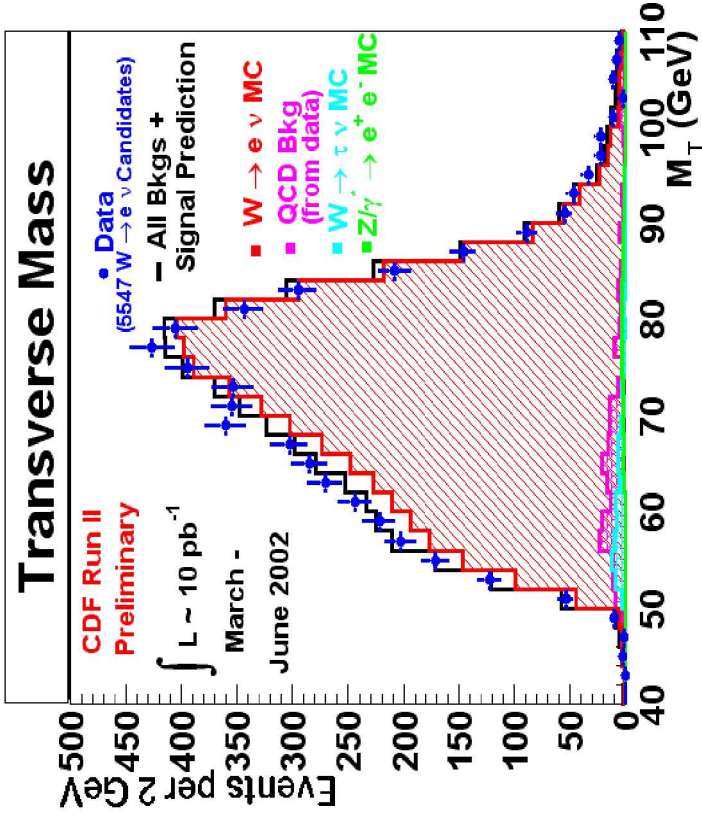- ee $\gamma\gamma$ MET event

- High E_t inclusive jet cross section

- "*Superjets*": excess in W+2,3 jet events with double b-tags

Ratio: Prel. data / NLO QCD (CTEQ5M | CTEQ5HJ)

CDF

CTEQ5M :   norm. facor :   1.00
CTEQ5HJ: 1.04

Incl. Jet : $p_t^7 * d\sigma/dp_t$

(Error bars: statistical only)
14% < Corr. Sys. Err. < 27%

Data / CTEQ5M
CTEQ5HJ / CTEQ5M
CDF Data (Prel.)
CTEQ5HJ
CTEQ5M

p_T

$W \to e\nu$, $W \to \mu\nu$ Cross Section

Good agreement of data and theory!

$W \to \mu\nu$: 4561 cand.

CDF Run II
$16\ pb^{-1}$
preliminary

- data
- all contributions
- $W \to \mu\nu$
- $Z \to \mu\mu$
- $W \to \tau\nu$
- QCD

entries per 3 GeV

transverse mass (GeV)

Transverse Mass

CDF Run II
Preliminary

$\int L \sim 10\ pb^{-1}$

March -
June 2002

- Data
  (5547 $W \to e\nu$ Candidates)
- All Bkgs +
  Signal Prediction
- $W \to e\nu$ MC
- QCD Bkg
  (from data)
- $W \to \tau\nu$ MC
- $Z/\gamma^* \to e^+e^-$ MC

Events per 2 GeV

M_T (GeV)
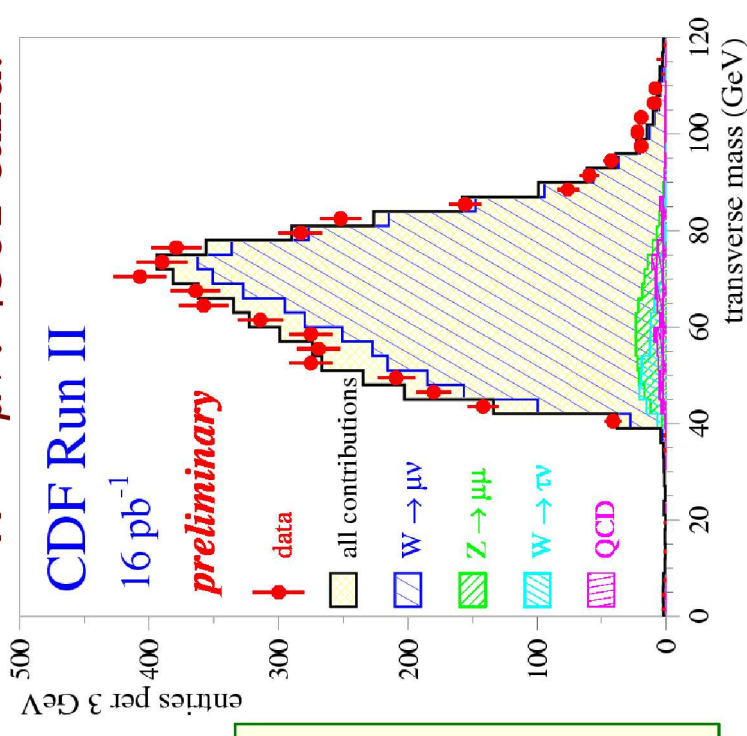
$\sigma \cdot BR(W \to e\nu) =$
$2.60 \pm 0.03\ (stat) \pm 0.13\ (syst) \pm 0.26\ (lum)\ nb$

$\sigma \cdot BR(W \to \mu\nu) =$
$2.70 \pm 0.04\ (stat) \pm 0.19\ (syst) \pm 0.27\ (lum)\ nb$

CDF Run I: $\sigma \cdot BR(W \to e\nu) =$
$2.49 \pm 0.12\ nb$ ($\sqrt{s} = 1.8$ TeV)

NNLO Theory (Stirling):
$2.50\ nb$ ($\sqrt{s} = 1.8$ TeV), $2.73\ nb$ ($\sqrt{s} = 1.96$ TeV)

February 10, 2003

Arnd Meyer (Fermilab)

Towards Top
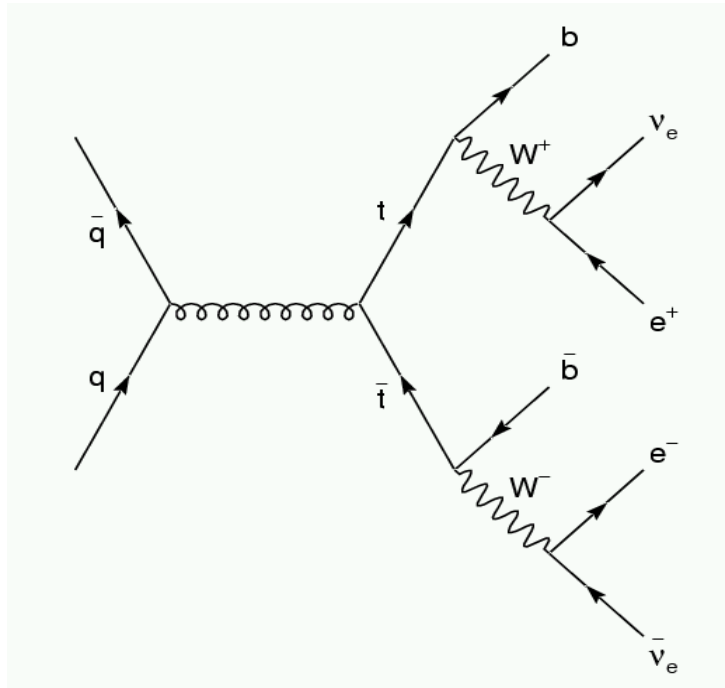
Top candidate event
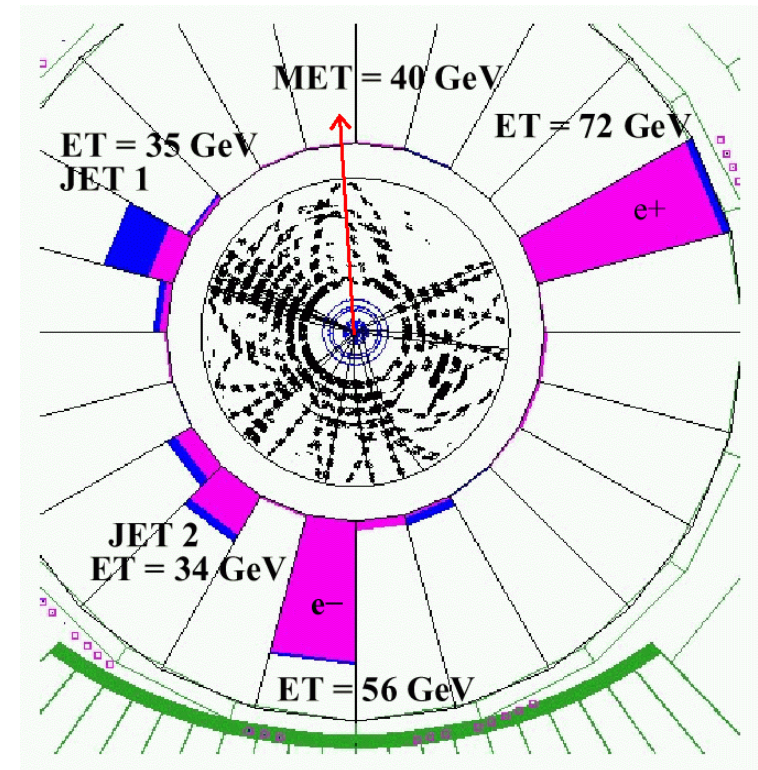
- Expect preliminary measurements of $t\bar{t}$ cross section by Spring 2003
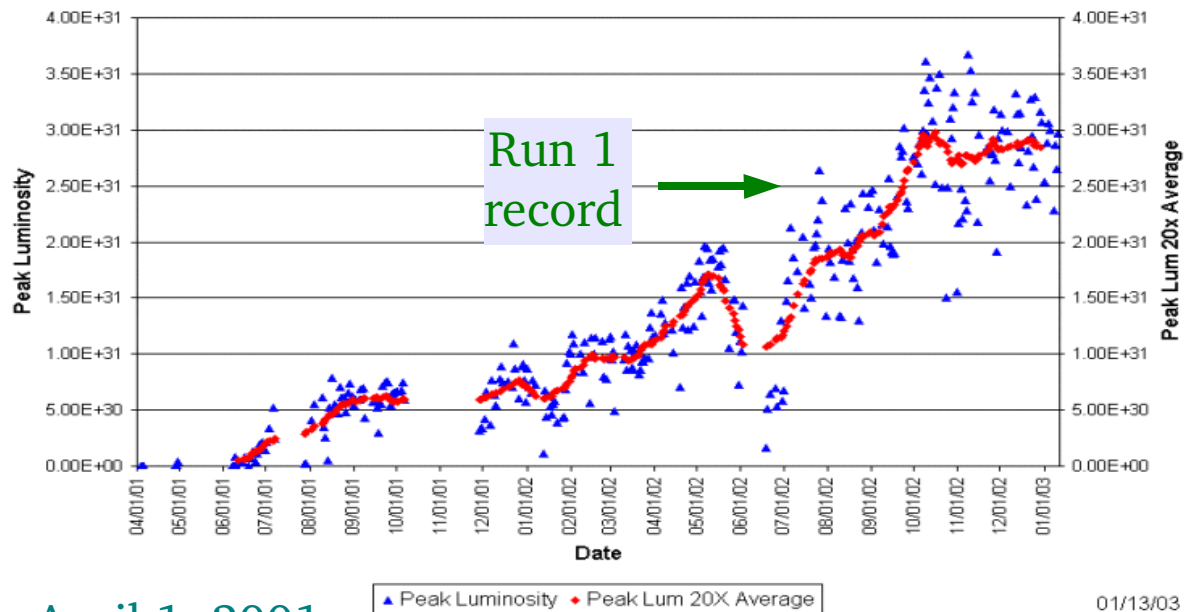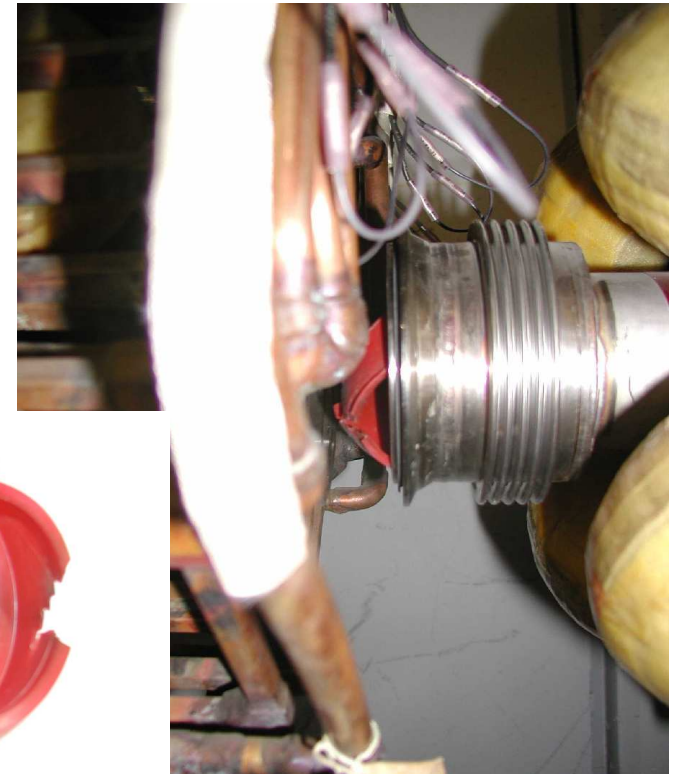
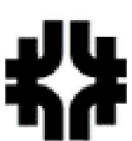# Shutdown Activities

Collider Run IIA Peak Luminosity

Run 1 record

April 1, 2001

Presently starting up
after 4 weeks
shutdown

Data Taking

- As of today, $\int L\,dt \simeq 170\ pb^{-1}$ delivered, CDF wrote 126 pb^{-1} to tape

- Since February 1st 2002, took (in runs with physics trigger tables)   **Typical rates:**

52,789,276,003	**L1 Accepts**	**9-12 kHz**
1,210,403,020	**L2 Accepts**	**200-300 Hz**
245,979,034	**L3 Accepts**	**30-55 Hz**

- We collect ~ 1 Terabyte of data on a good day (typical store duration 15 hrs)

Arnd Meyer (Fermilab)   February 10, 2003
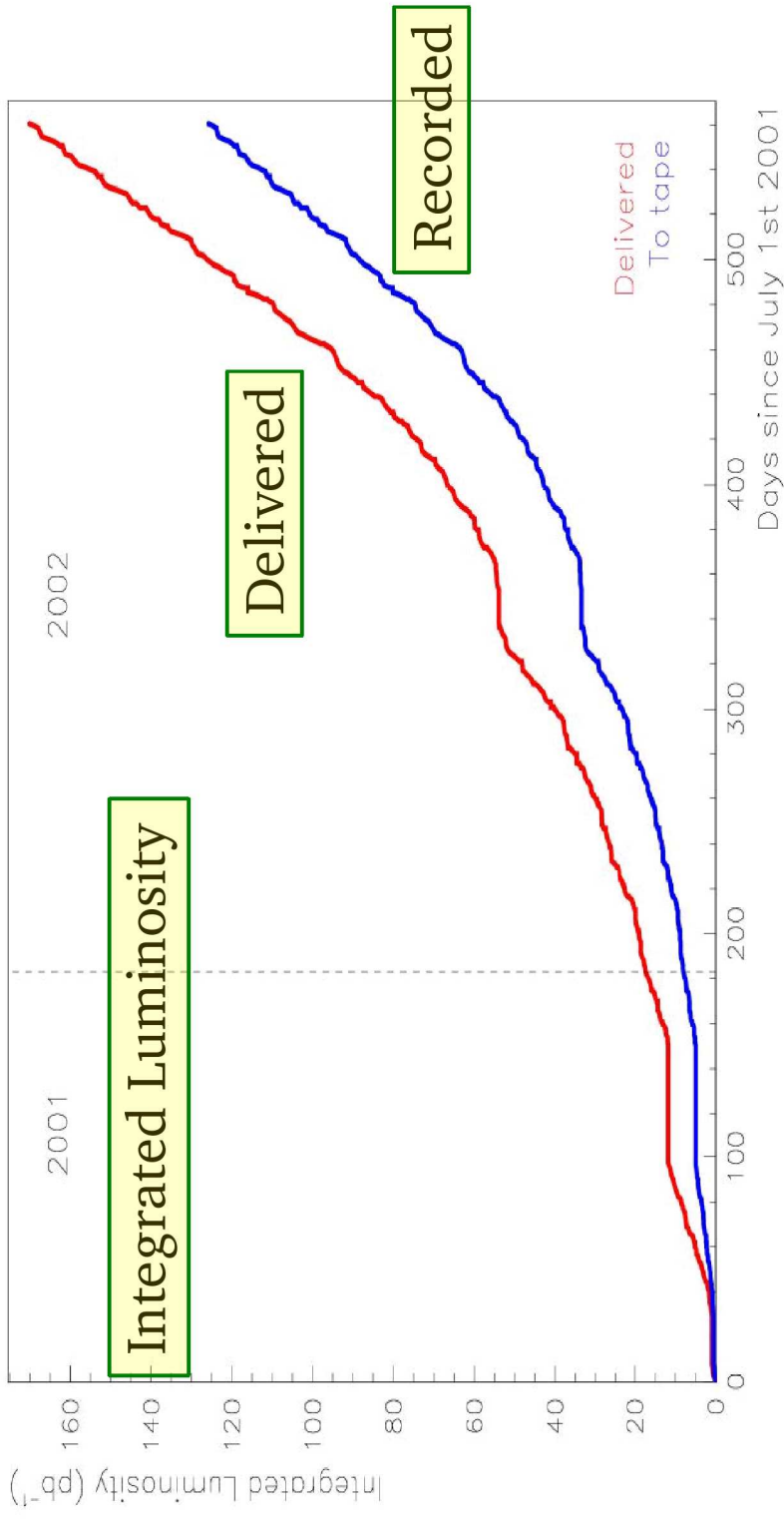
Summary

- **More than six years after the end of Run I, CDF can show the first physics results from Run II**

  - Masses, lifetimes, branching ratios etc. from b- and c-mesons

  - W, Z cross sections

  - ...

- After a slow startup, accelerator is beginning to show its potential

  - Recent performance improvements are encouraging - many problems have been identified and are being addressed, like bad transfer efficiencies, long range beam-beam effects in the Tevatron, large transverse emittance in the Accumulator, ...

- Early results also made possible by detector upgrades that allow previously impossible measurements

  - Prime example: hadronic B trigger. Tevatron+CDF provide an excellent charm factory.

- Exciting results will come out of the Tevatron experiments during the next 5 years
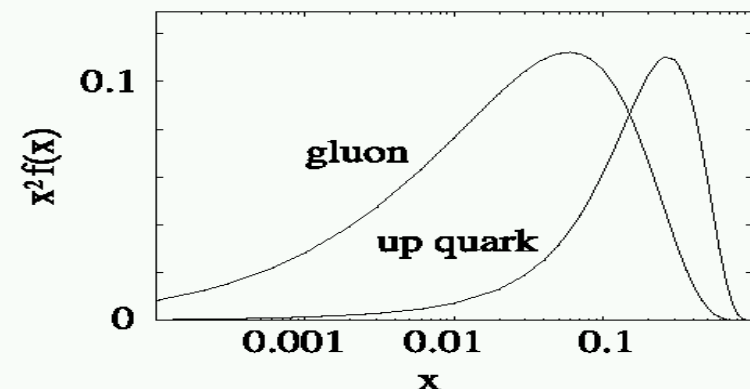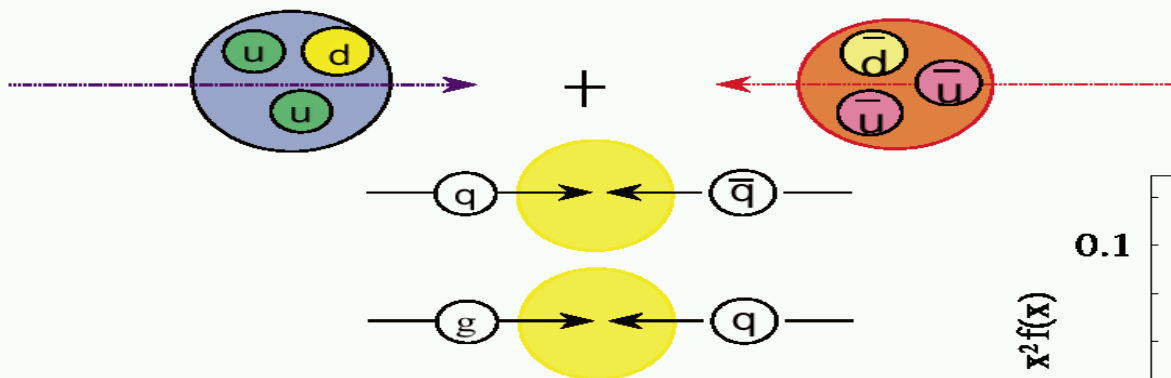
Hadron Collider Jargon

- Really colliding partons: qg, qq, gg

  - q can be a valence (u,d) or sea quark (...,s,c,b,...)

- Momenta given by Parton Distribution Functions (PDF's)

  - $p_t \equiv$ transverse momentum must balance

  - $p_z \equiv$ longitudinal momentum (along the beam) unknown

  - Coordinates (r, η, ϕ) with $\eta = -\ln(\tan(\theta/2))$ (pseudorapidity)

  - Distributions $dN/d\eta$ invariant under boosts in z

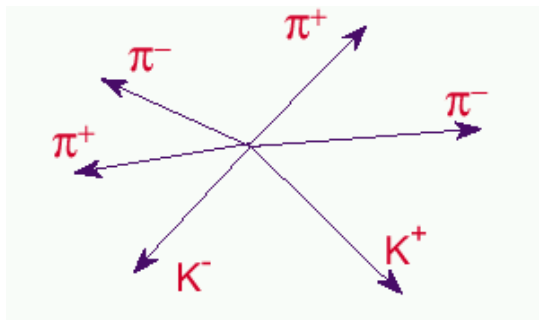Broadband: Production of particle states with cm energies from a few up to 100's of GeV

"Minimum Bias" vs. Hard Collisions

"Minimum Bias"

Quark-Antiquark-Annihilation
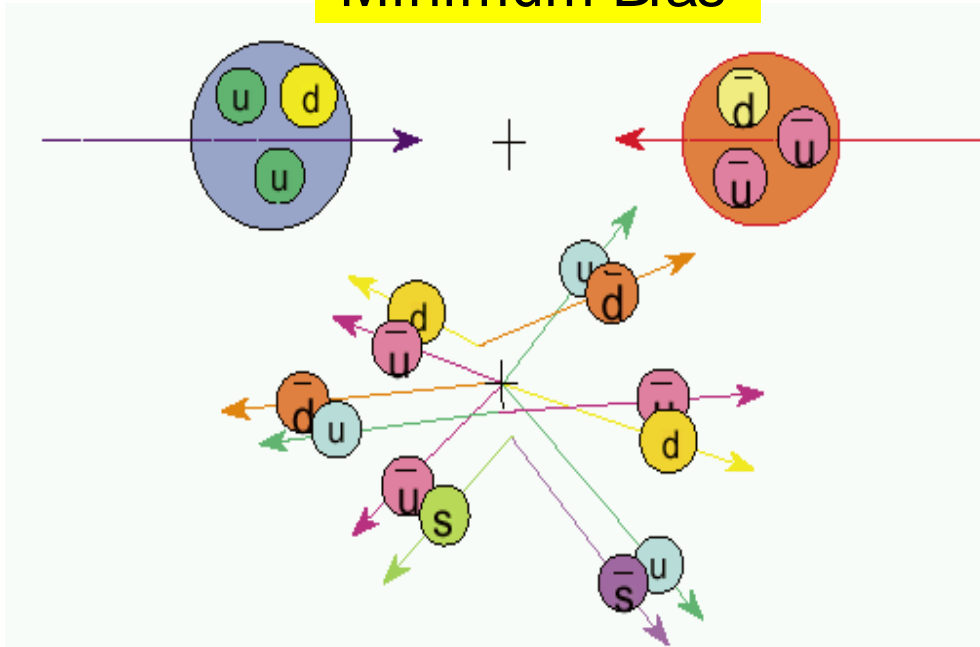
Vast majority of collisions, but not interesting...
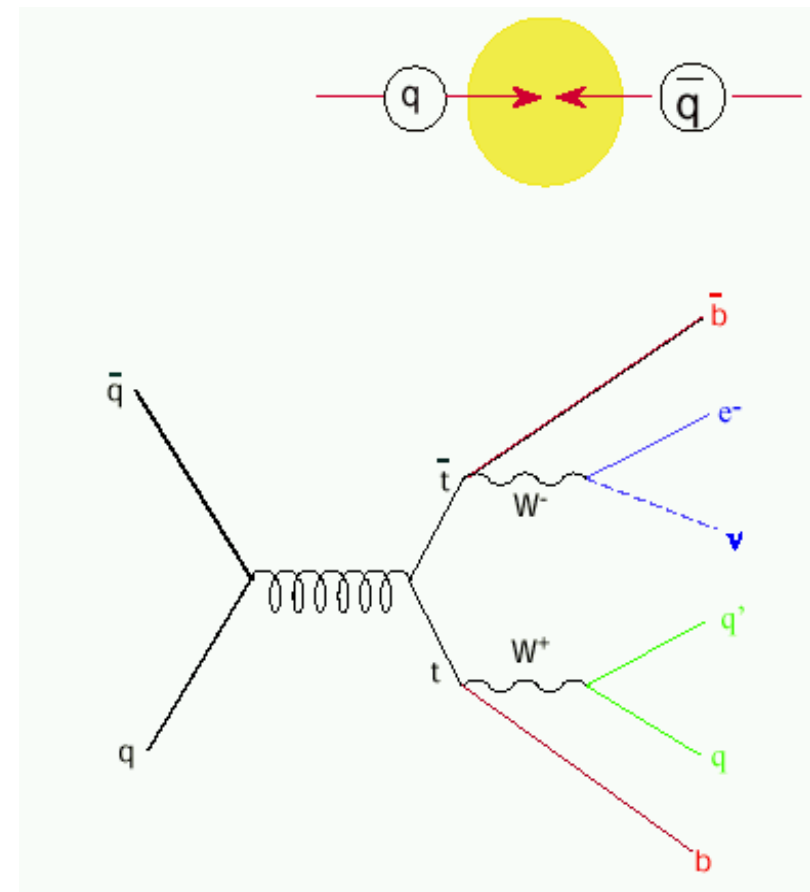
Example: top quark pair production

Hadron Collider Detectors

Muon detectors

Hadron calorimeter

Electromagnetic calorimeter

γ, π^0

μ^+

e^+

$K^+, \pi^+, p, \ldots$

$K^0 \rightarrow \pi^+\pi^-, \ldots$etc

Time of Flight

ν

1.4 T Solenoid

S i l i c o n D e t e c t o r

Drift Chamber
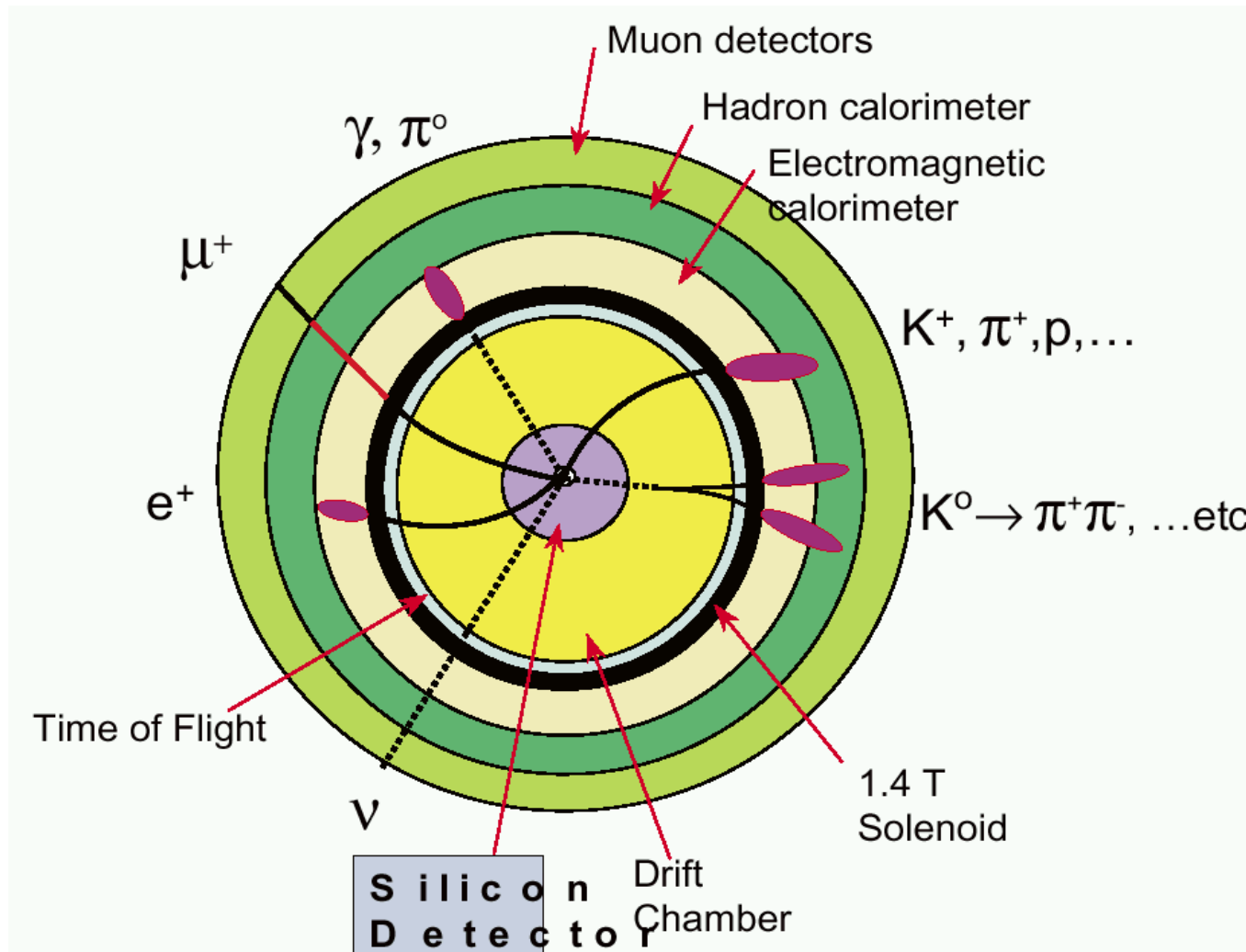
generic (u,d,s) jet

b,c,τ jet
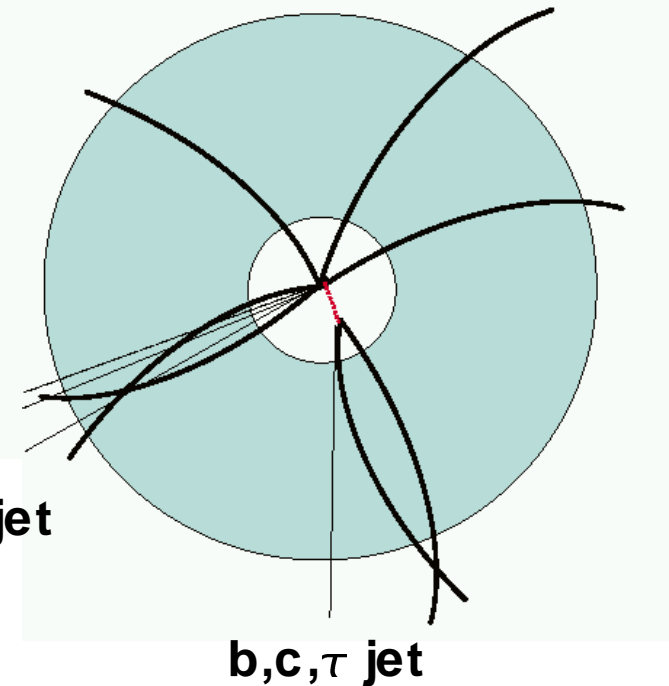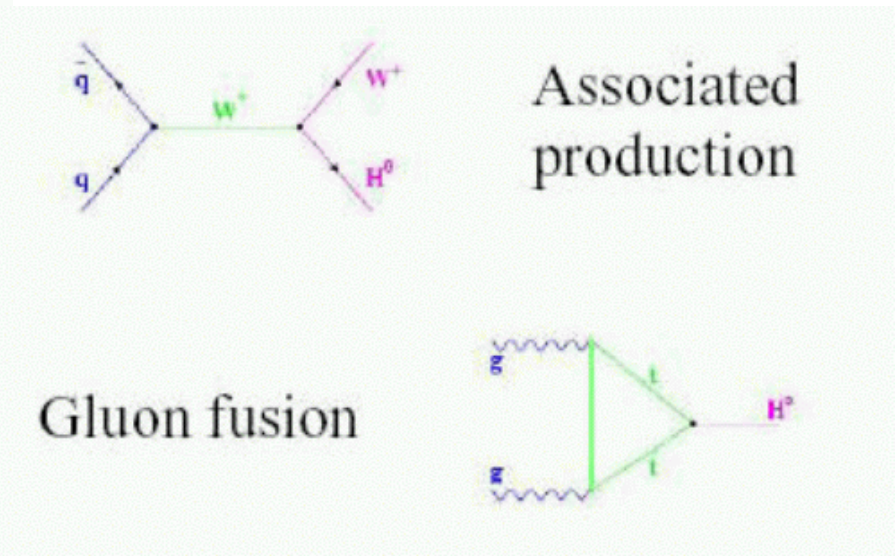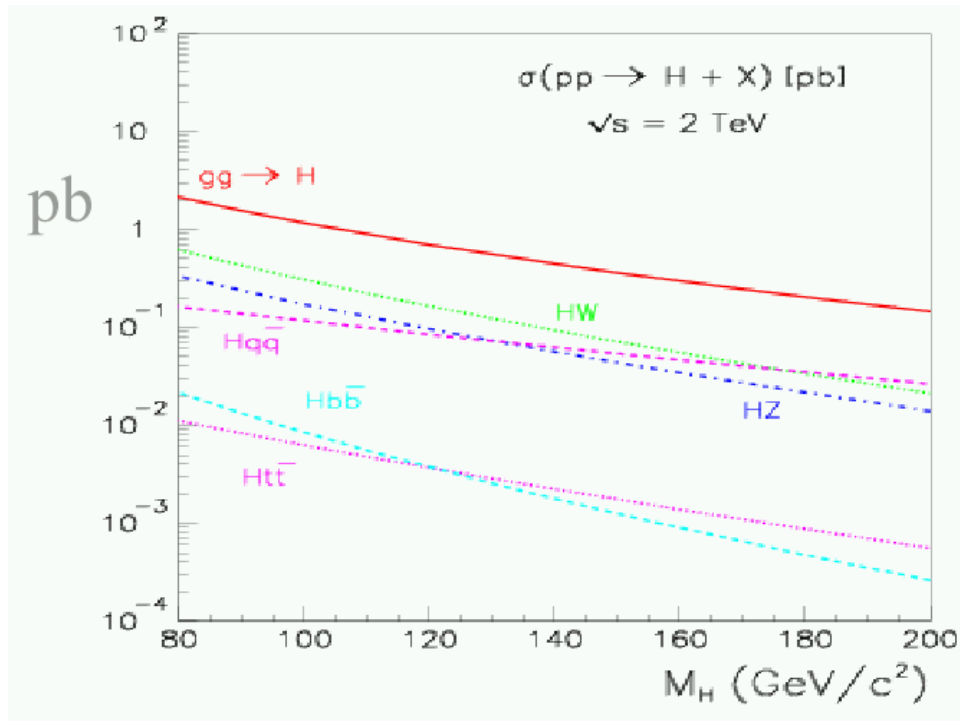
Higgs Production

- ♦ **gg → H dominates over all mass ranges**
  - – Difficult to trigger and reconstruct; swamped by QCD dijet production
- ♦ Main channel will be associated production, where the gauge boson can be used as a trigger

Higgs Boson Decay
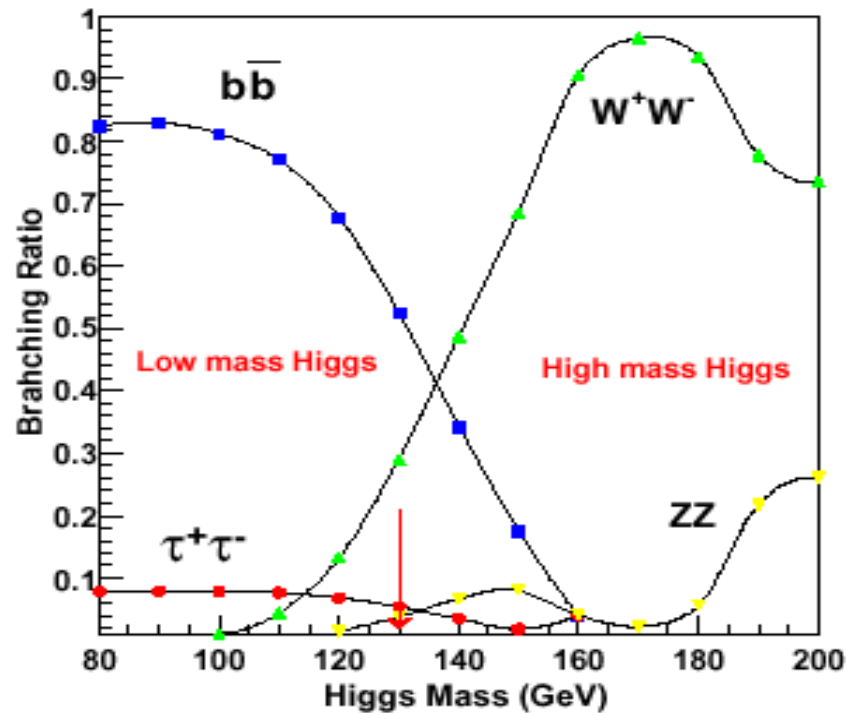
- **$M_H < 135$ GeV** (Low mass Higgs)

  - ♦ $H \to$ bbar with associated production mode is the most promising. The double b-tagging together with the signature of the additional boson helps to discriminate from the background.

- **$M_H > 135$ GeV** (High mass Higgs)

  - ♦ Exploit gluon fusion, and reconstruct the two gauge bosons

- In general, luminosity is critical
- Plus, we haven't even started to build the detector to go well above 2 fb^{-1}

CDF Run II B Physics Goals

"High profile" analyses

- CP violation (oh well...)

  ♦ Improved measurement of $\sin(2\beta)$ in $B^0 \to J/\psi\, K^0_s$: $\simeq 20000$ events in 2 fb^{-1}

    $\sigma(\sin2\beta) \simeq 0.05$

- B_s mixing in $B_s \to D_s\pi^+/D_s\pi^+\pi^-\pi^+$, sensitivity up to about

    $x_s \simeq 60$ ($\simeq 75000$ events)

    $x_s \simeq 30$ in semileptonic decays

    ($x_s = \Delta m_s / \Gamma_s$)
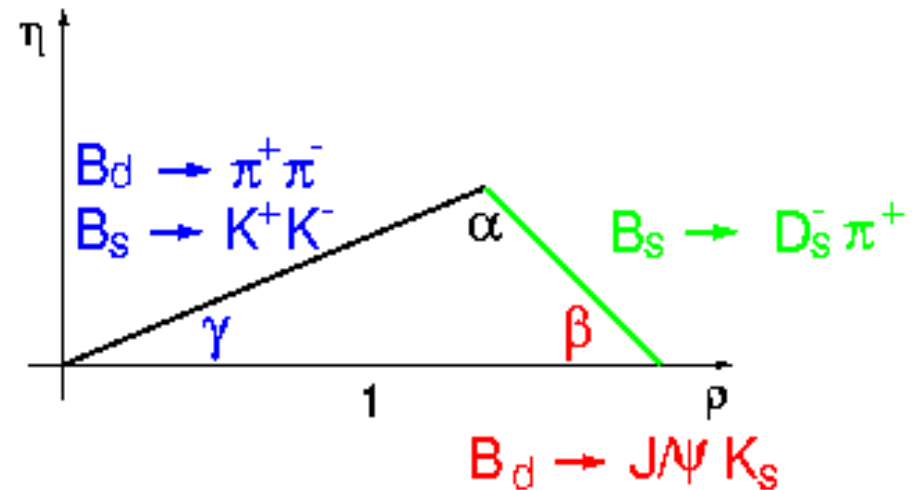
- Measurement of γ in $B^0_d \to \pi^+\pi^-$ and $B^0_s \to K^+ K^-$ decays

  ♦ Use of both decays reduces the influence of penguins

  ♦ Assuming S/B = ½ and $\Delta m_s = 30$ ps^{-1} events: 5000 ($\pi^+\pi^-$) / 10000 (K$^+$K)

    $\sigma(\gamma) \simeq 7^0$

Why B Physics at the Tevatron?

- **Huge cross section**

  - $\sigma(\text{ppbar} \to \text{bbar})$ $\simeq$ **150 μb** at $\sqrt{s}$ = 2 TeV (15 kHz at L = 10^{32}cm^{-2}s^{-1})
    50 μb for $|\eta| < 1$

  - $\sigma(e^+e^- \to \text{bbar})$ $\simeq$ **7 nb** at Z^0

  - $\sigma(e^+e^- \to \text{bbar})$ $\simeq$ **1 nb** at $\Upsilon(4S)$

- **Produce bottom mesons with all flavor combinations as well as bottom baryons**

  - B_c, Λ_b, Σ_b, ... no competition from B factories

- **Multipurpose detector capable of reconstructing many B final states**

  - Very large tracking volume

- **DAQ / trigger / particle ID are tailored for B physics!**

  - Up to 50kHz Level 1 accept rate!

  - Trigger on displaced vertices at Level 2

  - Time-of-Flight detector for K tagging

Tracking

CDF RunII preliminary
11 pb^{-1}

Silicon selection
53k signal events
width = 14.9 MeV

Events/5 MeV

μμ mass [GeV]

CDF candle: J/ψ $\to$ $\mu\mu$

- J/ψ width: 22 MeV (only COT)
  15 MeV (add Silicon)

- Visible cross section $\simeq$ 9nb (CMU only)

- ◆ Sharp trigger turn-on p$_t$>1.5GeV
  (Run 1: 2.2GeV, slow turn-on)

- ◆ Di-μ trigger efficiency $\simeq$ 90%

- Invaluable for tracking studies, tuning, B physics, ...
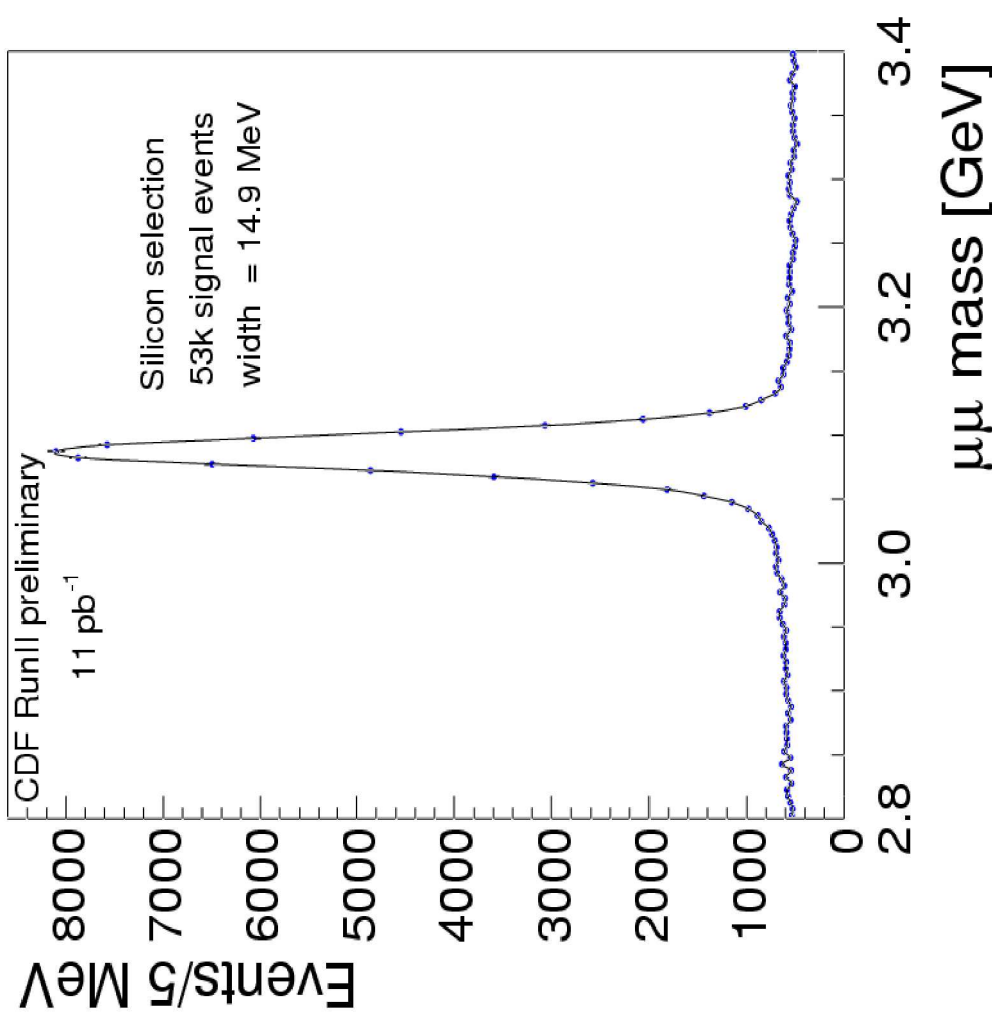
Note: "J/ψ" implies "J/ψ $\to$ $\mu\mu$" for the rest of this talk

Search for η_b (new Run I result)

- Lightest member of the Bottomonium family - **good chance to be discovered early in Run II**

- Most promising decay mode is to $J/\psi\ J/\psi$

- Run I: found a 2.2 σ (1.5%) excess, using $\mu\mu\mu$+track search strategy

- Lower trigger threshold and improved acceptance will help in Run II

Run II Physics Program

15 fb⁻¹

- 5σ Higgs signal @ $m_H = 115$ GeV
- 3σ Higgs signal @ $m_H = 115$-135, 150-175 GeV
- Reach ultimate precision for top, W, B physics

10 fb⁻¹

- 3σ Higgs signal @ $m_H = 115$-125, 155-170 GeV
- Exclude Higgs over whole range of 115-180 GeV
- Possible discovery of supersymmetry in a larger fraction of parameter space

5 fb⁻¹

- 3σ Higgs signal @ $m_H = 115$ GeV
- Exclude SM Higgs 115-130, 155-170 GeV
- Exclude much of SUSY Higgs parameter space
- Possible discovery of supersymmetry in a significant fraction of minimal SUSY parameter space (the source of cosmic dark matter?)

2 fb⁻¹

- Measure top mass ± 3 GeV and W mass ± 25 MeV
- Directly exclude $m_H = 115$ GeV
- Significant SUSY and SUSY Higgs searches
- Probe extra dimensions at the 2 TeV (10^{-19} m) scale
- B physics: constrain the CKM matrix

300 pb⁻¹

- Improved top mass measurement
- High p_T jets constrain proton structure
- Start to explore B_s mixing and B physics
- SUSY Higgs search @ large $\tan\beta$
- Searches beyond Run I sensitivity

Each gain in luminosity yields a significant increase in reach and lays the foundation for the next steps